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TRANSPORTATION NOISE AND NOISE FROM EQUIPMENT POWERED BY INTERNAL COMBUSTION ENGINES

DECEMBER 31, 1971

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DECEMBER 31, 1971

Prepared by

WYLE LABORATORIES
under
CONTRACT 68-04-0046

for the

U.S. Environmental Protection Agency
Office of Noise Abatement and Control
Washington, D.C. 20460

This report has been approved for general availability. The contents of this report reflect the views of the contractor, who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of EPA. This report does not constitute a standard, specification, or regulation.

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1.0 INTRODUCTION

The outdoor noise environment for man today is the summation of noise energy generated by all of the machines used to transport people and goods, machines used to make and build things or save human labor, machines used by the consumer for leisure activity, machines to make the other machines run, and people in their various activities. Development of this machinery has been fostered by growth in technology itself, as well as by pressures induced by changes in our life style and by population growth. This report presents a detailed evaluation of noise of transportation vehicles including those used commercially, as well as many of the private and non-industrial devices powered by internal combustion engines.

The report has been prepared by Wyle Laboratories for the Environmental Protection Agency in response to the directives contained in the Clean Air Amendments Act of 1970, specifically, Section 401 "Noise Pollution and Abatement Act of 1970." It forms part of the major study accomplished by the Office of Noise Abatement and Control, of the Environmental Protection Agency, which is summarized in its report to Congress.[1*]

The noise sources considered in this report are encountered throughout man's residential, recreational and working community. Sound is important to most of the animal kingdom, including man. Some sounds provide warnings of danger, which are essential for survival. These sounds may evoke basic reactions of startle, fear or anger, which in turn assist in causing an appropriate response. Acoustic warning devices such as sirens and horns utilize this principle, and the noise of an approaching automobile is often the first clue of danger to the pedestrian or the child playing ball in the street.

Other sounds evoke pleasure or are generated by an animal to reinforce or communicate pleasure. The purring of a kitten and the ecstatic shouts of a child at play are familiar examples to all. Some pleasant sounds are relaxing, lulling an animal to sleep, and others are stimulating. Music, developed by man, covers this broad spectrum, appealing to a wide variety of desires and needs at both the basic and intellectual levels.

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* Throughout this report, references are identified by superscripts.

For man, sound has even more importance. His ability to communicate by speech is the keystone of civilization and its spiritual, social, political, economic and technical progress. Without speech communication, man would never have emerged from a primitive state and developed the body of knowledge which could be passed from generation to generation. Nor would he be able to interact with his fellow man in anything beyond the most rudimentary levels such as are displayed by the higher primates.

The undesirability or desirability of noise in the environment must be judged with reference to its effects on man's basic and intellectual perceptions and actions. Noise is undesirable when it causes impairment of hearing acuity, interferes with speech communication, causes unnecessary distraction, or warns of danger when none is present. However, noise is desirable when it provides a relatively steady background which masks unwanted distractive sounds, or provides speech privacy so that others do not overhear a private conversation. Consequently, the goals for noise control must be designed such that the desirable qualities are retained and the undesirable qualities are minimized. This is a most difficult task, particularly with transportation noise which provides the all-pervasive almost steady outdoor residual noise level essential for speech privacy, and also is responsible for many of the most intrusive and undesirable noises.

To provide a clear understanding of the significance of noise from these sources on our environment, several aspects are considered in this report:

- Nature and economic significance of the industry associated with the source.
- Basic noise characteristics of each type of source.
- Environmental noise attributes of each type of source.
- Past and present efforts toward reducing noise.
- Estimated potential noise reduction for the future with today's technology.

Chapter 2 presents these findings for all types of vehicles in our transportation system, including those used for recreation. Chapter 3 considers these same aspects for many of the devices powered by internal combustion engines. This overview of the existing and potential noise characteristics of these sources provides the basis for an assessment of the impact of their contribution to our total noise environment which is presented in Chapter 4. The impact is discussed from several viewpoints for each basic source type in our transportation system, as well as for internal combustion engine devices, and a projection is made of possible future impact to the year 2000. Finally, the implications of the overall results of this study are summarized in Chapter 5 and recommendations made for further action to reduce the overall noise impact of the noise sources considered.

Appendix A summarizes several of the more significant national standards for noise measurement or control which are applicable to this report. It includes a copy of pertinent sections of Federal Aviation Regulation (FAR) Part 36 – Noise Standards: Aircraft Type Certification. This regulation represents the most complete and comprehensive noise measurement and noise regulation standard ever developed by the Federal Government and is playing a major role in fostering development of quieter non-military jet aircraft.

Appendix B presents in more detail the basis for the various impact evaluation models utilized in Chapter 4. Appendix C gives a detailed discussion of the principal sources which dominate the noise generation by all of the systems or devices considered in this report. These are the propulsion systems of aircraft and motor vehicles, including turbojets, turbofans, propellers, rotors, reciprocating engines and tires.

Throughout this report, single-number noise levels are commonly specified in terms of A-weighted noise levels in decibels, abbreviated dB(A), defined in Appendix B. The A-weighted sound (or noise) level is the most commonly-used single-number scale for quantifying approximately the subjective noisiness of sounds, particularly those from vehicles other than aircraft. It is also readily measured with the use of a standard sound level meter employing the A-weighting network. Other single-number scales for evaluating aircraft noise are introduced as necessary. Where appropriate, frequency content of the noise generated by the various sources are specified in terms of octave or one-third octave band sound pressure levels in decibels relative to 20 newtons per square meter (equivalent to 0.0002 dynes/cm^2).

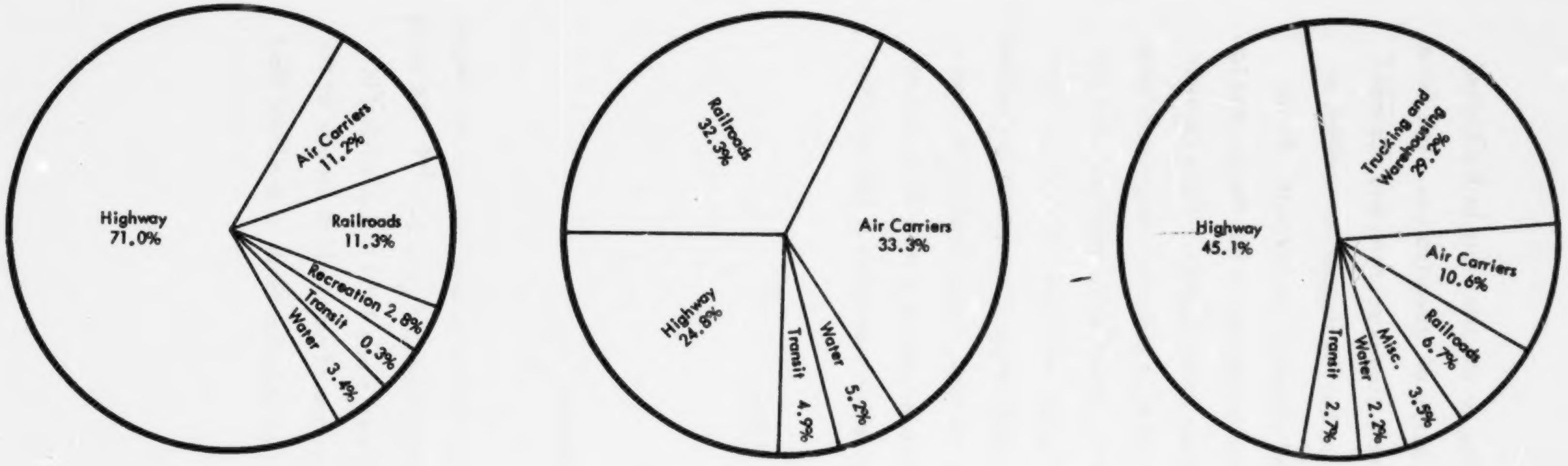
2.0 TRANSPORTATION SYSTEMS

One of the most significant forces acting on the life style in the United States is the ever-increasing demand for improved modes of transportation. This force is, in itself, a natural product of the pressure of increasing population and economic growth. As the size of urban areas has increased, so has the demand for methods of transporting people to and from their residences and places of employment. As the interdependency between and within urban areas has increased, so has the demand for transporting goods and services between and within our urban centers. These demands have been met by an ever-increasing development of more efficient, larger and faster modes of transportation. First, the steam locomotive, then the automobile, next the propeller airplane, and most recently, the jet transport – all have acted to transform the structure and style of our lives by providing a wide range of transportation methods.

The transportation industry represents, in total, approximately 14.5 percent of the gross national product in 1970 and employed approximately 13.3 percent of the total labor force. This major section of the nation's economy is defined, for this report, as the sum total of the:

- Commercial aircraft and airline industry
- General aviation industry
- Highway vehicle industry
- Recreational vehicle industry
- Railroad and urban mass transit industry
- Commercial shipping industry

The economic structure of this industry and the general division and magnitude of the transportation services provided are illustrated in Figure 2-1.[1-6] The rapid growth of several segments of the transportation system since 1950 is summarized in Table 2-1.[1-6] While there are many important sources of noise which intrude on our everyday lives, noise from all types of transportation vehicles tends to dominate most



Transportation Service and Equipment Product
($145 Billion in 1970)

Transportation Service and Equipment
Capital Investment
($114 Billion in 1970)

Transportation Service and Equipment Employmunt
(11.3 Million in 1970)

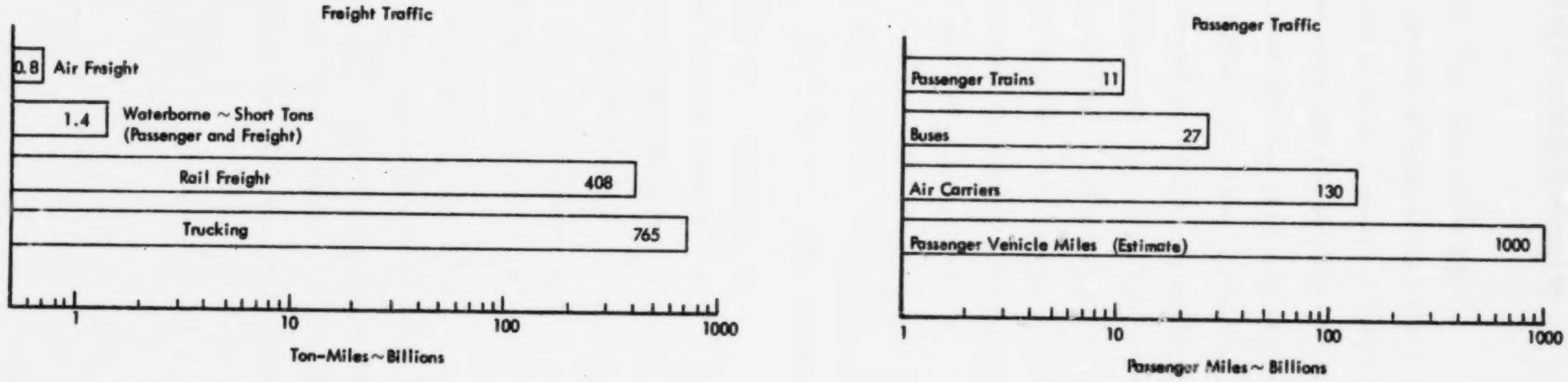


Figure 2-1. General Characteristics of the Transportation Industry in 1970

Table 2-1

Growth in the Transportation System, 1950-1970

Source	1950	1960	1970
Population (in millions)	151	181	204
Passenger Cars (in millions)	40.4	61.7	87.0
Trucks and Buses (in millions)	8.8	12.2	19.3
Motorcycles (in millions) (Highway)	0.45	0.51	1.2
Motorcycles (in millions) (Off-road)	-	-	1.8
Snowmobiles (in millions)	0	0.002	1.6
2-3 Engine Turbofan Aircraft	0	0	1174
4-Engine Turbofan Aircraft	0	202	815
General Aviation Aircraft	45,000	76,200	136,000
Helicopters	85	634	2800

residential areas. In fact, the cumulative effect of the increase in noise intrusion by transportation vehicles is, to a large extent, responsible for the current concern with noise pollution. This section briefly describes the general nature of transportation system noise sources and considers their overall impact in the United States today. Aircraft, one of the more dominant sources of noise in the transportation industry, will be considered first.

2.1 Commercial Aircraft

2.1.1 Introduction

There has been a significant increase in air travel during the last decade which is closely related to the introduction and growth of the commercial jet aircraft fleet. Since 1958, when the first commercial jet aircraft started operating, passenger air travel has grown at an average annual rate of 13.2 percent, to a total of 132 billion passenger miles in 1970. In 1970, 170 million passengers were flown by the airlines, producing an operating revenue of $7.6 billion. In addition, 5 billion ton-miles of air freight were transported for a revenue of $715 million. The scheduled airlines employed 300,000 people. The aerospace and related manufacturing industries employed 765,000 people and had a total of $8.6 billion in commercial aircraft sales.[1,2]

The advantages of jet-powered passenger airplanes – greater speed and reduced operating cost per passenger-mile – have led to a gradual phasing out of the older propeller-driven commercial aircraft. Only a small percentage of piston-powered aircraft now remains in the fleet, and the turboprop aircraft in use are primarily short range twin-engine types used on light traffic routes.

The original commercial jet aircraft were powered by turbojet engines. These engines have been largely replaced by quieter and more powerful turbofan engines. There are two basic types of jet aircraft in the current commercial fleet. The first type is the 4-engine turbofan aircraft such as the Boeing 707 and 720 and the McDonnell-Douglas DC-8. These aircraft are used primarily on medium and long range flights and are almost exclusively powered by first-generation turbofan engines. The second basic aircraft type is exemplified by the Boeing 727 and 737 and the McDonnell-Douglas DC-9. These aircraft are powered by two or three more advanced and quieter turbofan engines and are used on short and medium range flights.

Two new types of commercial jet aircraft have recently been introduced in the fleet. These are powered by advanced technology turbofan engines that are much more powerful and quieter than engines used in the previously mentioned aircraft types. The 4-engine 747 widebody jet, introduced in 1969, is intended for long range transcontinental and intercontinental flights. The 3-engine widebody aircraft, DC-10 and L-1011, will be used on high density, medium length flight routes.

Figure 2.1-1 summarizes the category of commercial aircraft in terms of type, application, passenger capacity and noise.[2-13]

2.1.2 Source Noise Characteristics

The noise associated with jet aircraft is primarily generated by the jet engines. Noise is an operational by-product of these powerplants. The primary purpose of a jet engine is to produce the thrust necessary to push the aircraft through the air. A jet engine produces thrust by taking in air through the inlet, raising the air temperature and pressure inside the engine, and then expelling it to the rear with a high velocity from the jet nozzle. Noise is produced by several of the processes that take place both within and outside the engine. By far the dominant source of noise from the early turbojet engines was the broadband jet noise generated in the exhaust wake. Jet noise is caused by the turbulent mixing that occurs along the boundary between the high velocity exhaust jet and the ambient air. The sound power generated increases very rapidly with increasing jet velocity, hence the high noise levels are associated with the high velocity exhausts of turbojet engines.

The turbofan engines that have replaced the turbojets offer substantial jet exhaust noise benefits because they take in larger quantities of air and expel this air at lower jet velocities. This change has been accomplished by the use of a fan section in the engine that takes in air, raises its pressure, and expels it through a separate nozzle, thus bypassing the burner and turbine sections of the engine with part of the total airflow. However, with reduced levels of jet noise and with a noise radiation path rearward out the fan duct and forward out the inlet, fan whine was elevated from a secondary noise source to one of dominant importance, particularly at approach powers.

Figure 2.1-2 shows typical noise levels and spectra measured during takeoff and approach operations for 4-engined aircraft with low bypass engines.[5] The engine thrust, and thus the jet exhaust velocity, is higher during takeoff than during approach

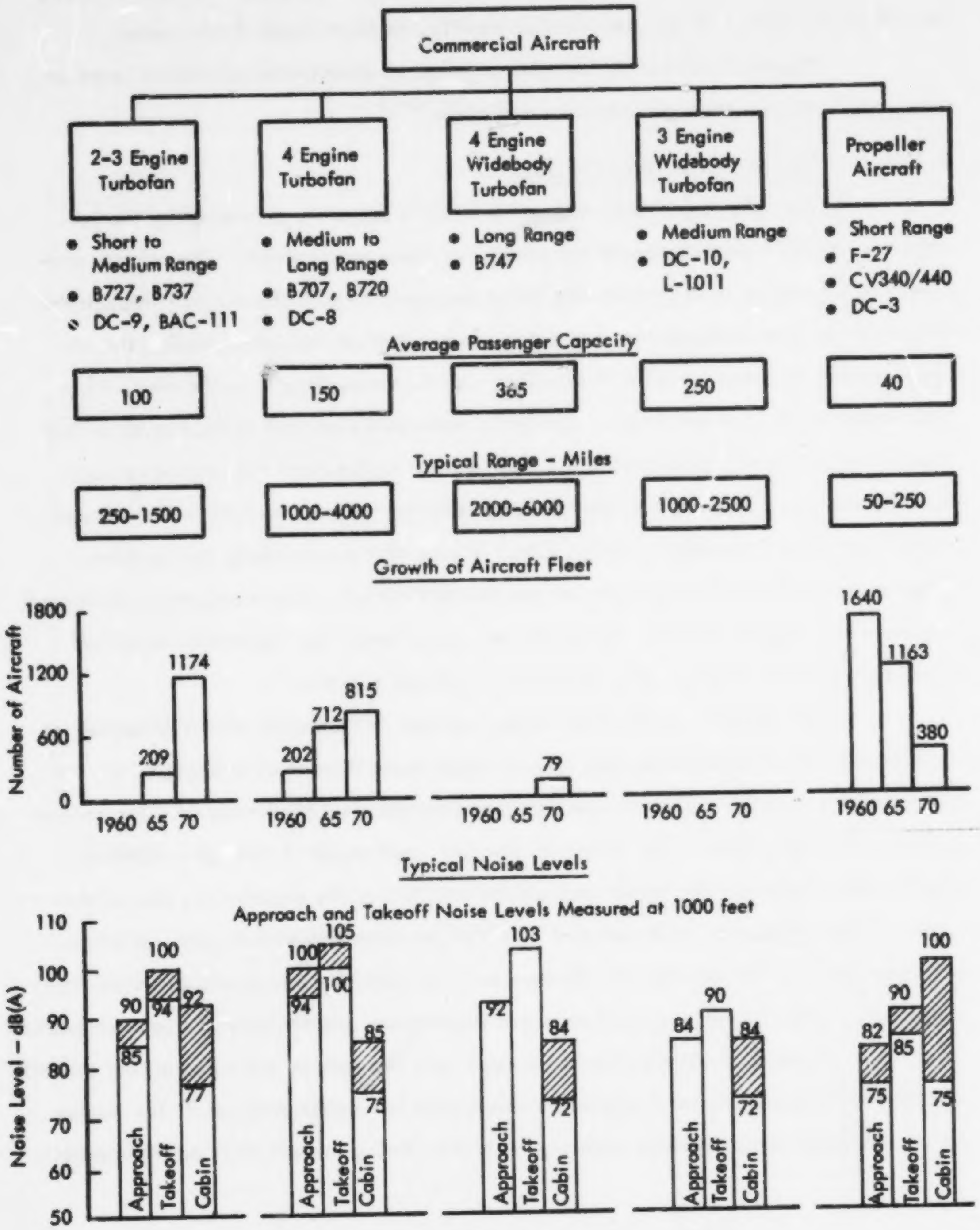


Figure 2.1-1. Characteristics of Commercial Aircraft

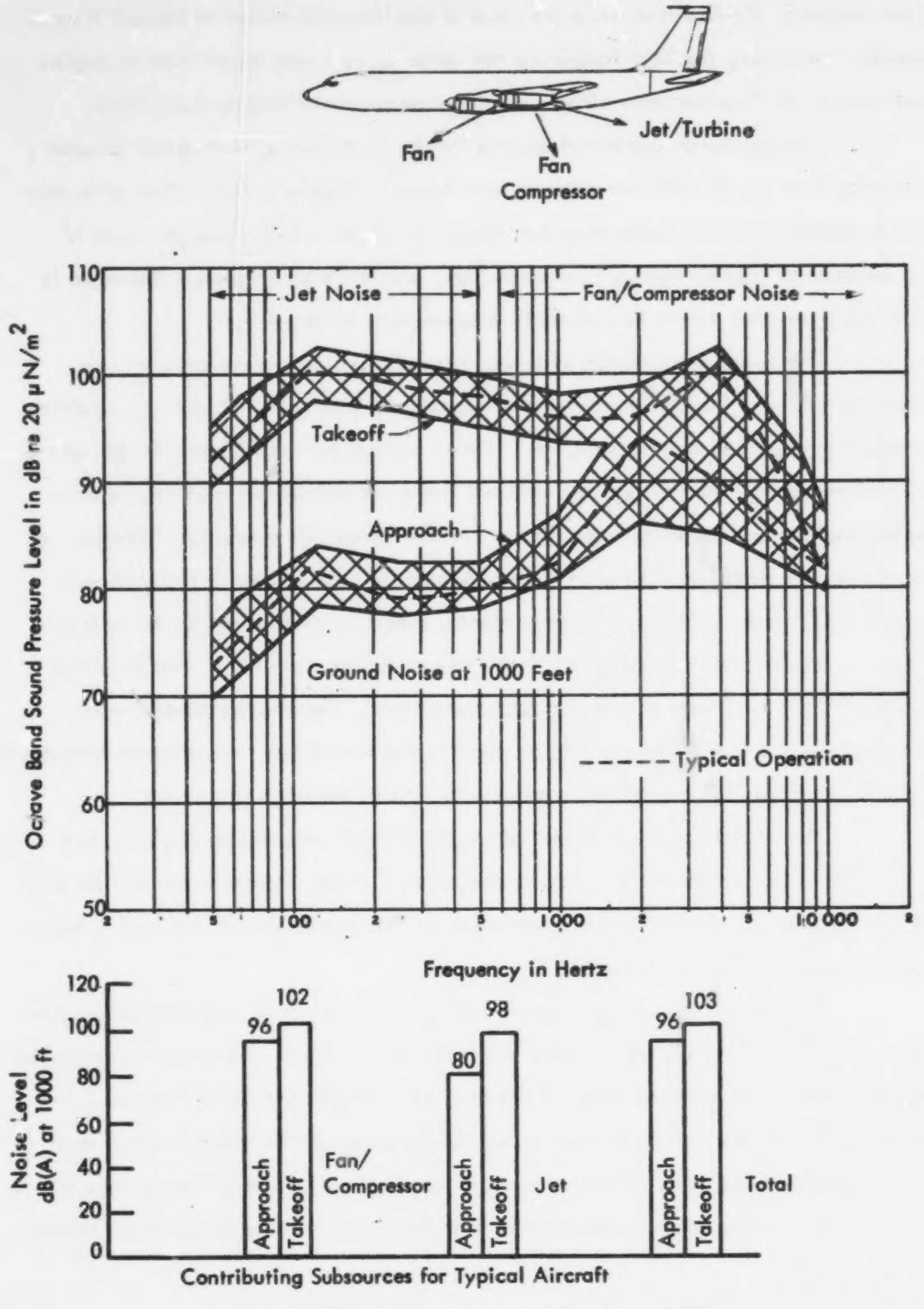


Figure 2.1-2. Noise Limits and Spectra of 4-Engine Low Bypass Ratio Turbofan Aircraft

and consequently the low frequency jet noise is significantly higher at takeoff than at approach. However, the high frequency fan noise is relatively insensitive to engine power setting and thus becomes clearly dominant at approach engine conditions.

Typical noise levels and spectra for the 2- to 3-engine turbofan aircraft, powered by later model turbofan engines, are shown in Figure 2.1-3.[5] The noise produced by these aircraft is lower than that shown in Figure 2.1-2. The jet noise is lower because of slightly reduced jet velocities, and the high frequency fan noise is considerably reduced due to fundamental improvements in fan design.

The 4-engine turbofan widebody aircraft, which are powered by new technology engines, incorporate several advancements both with respect to propulsion efficiency and reduced noise generation. These engines pass a high percentage of the total airflow through the fan section, and are therefore considered high bypass ratio turbofan engines in comparison with the earlier low bypass ratio engines. The low jet exhaust velocity made possible with these new engines has resulted in a significant reduction in jet noise. This reduction is clearly shown by comparing the noise levels and spectra presented in Figure 2.1-4 with those of Figure 2.1-3.[5-8] The fan noise dominates both during takeoff and approach operations. Despite the considerable technological advances that were incorporated in the fan design, the discrete frequency fan whine forms the major obstacle to achieving significant noise reduction.

The new 3-engine turbofan widebody aircraft uses similar engines, but with additional improvements in fan noise reduction. These improvements will be discussed in Section 2.1.4 and further information on the mechanisms of jet engine noise generation may be found in Appendix C .

The noise generated by commercial propeller aircraft is dominated by propeller noise. Typical noise spectra and levels for various types of commercial propeller aircraft are compared with the noise of the original turbojet aircraft in Figures 2.1-5 and 2.1-6.[14] The increase in aircraft noise which occurred with the introduction of the jets is evident. Because propeller aircraft constitute such a small percentage of commercial aviation aircraft, especially so with respect to their relative noise impact,

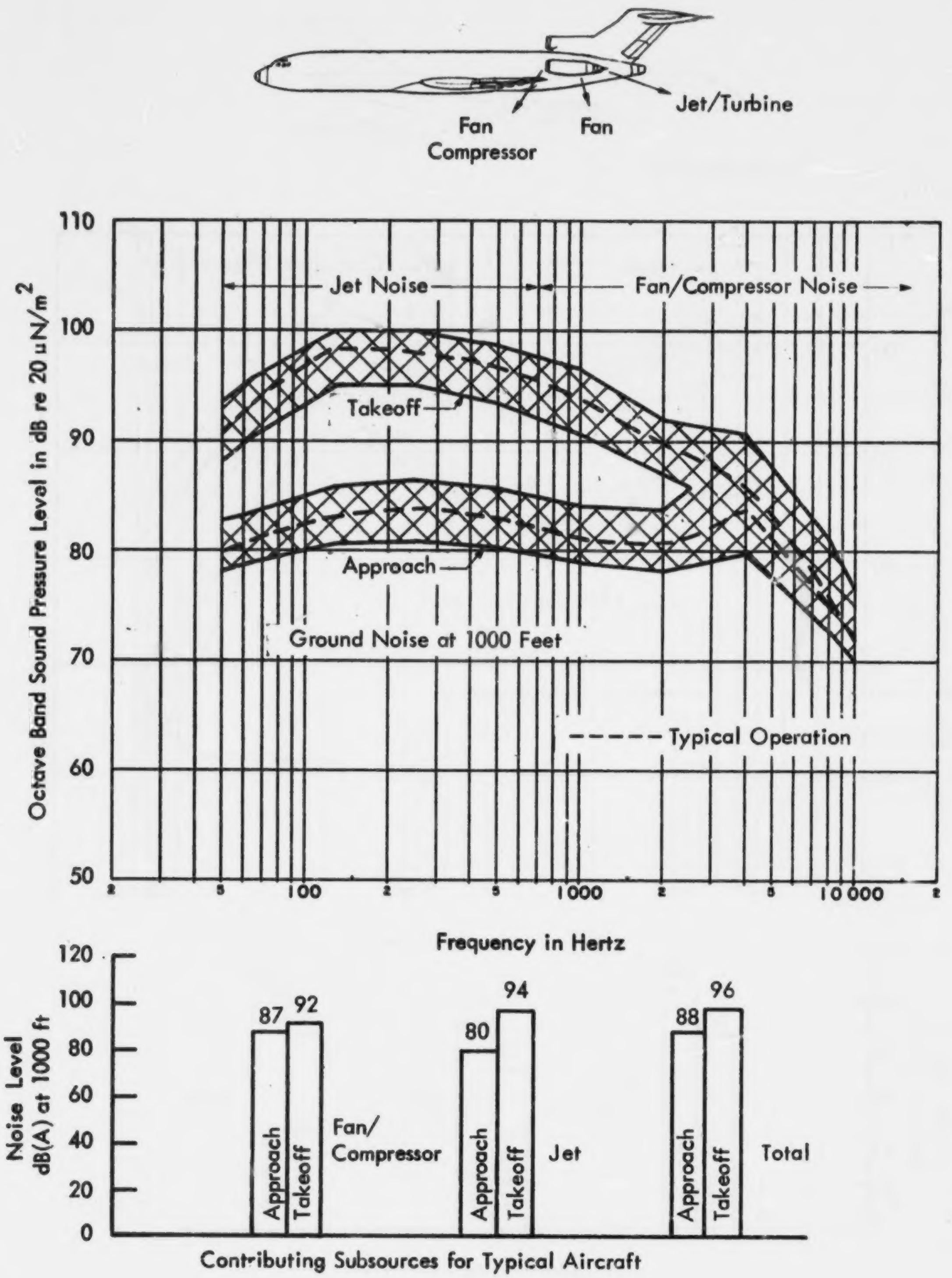


Figure 2.1-3. Noise Levels and Spectra of 2-3 Engine Low Bypass Ratio Turbofan Aircraft

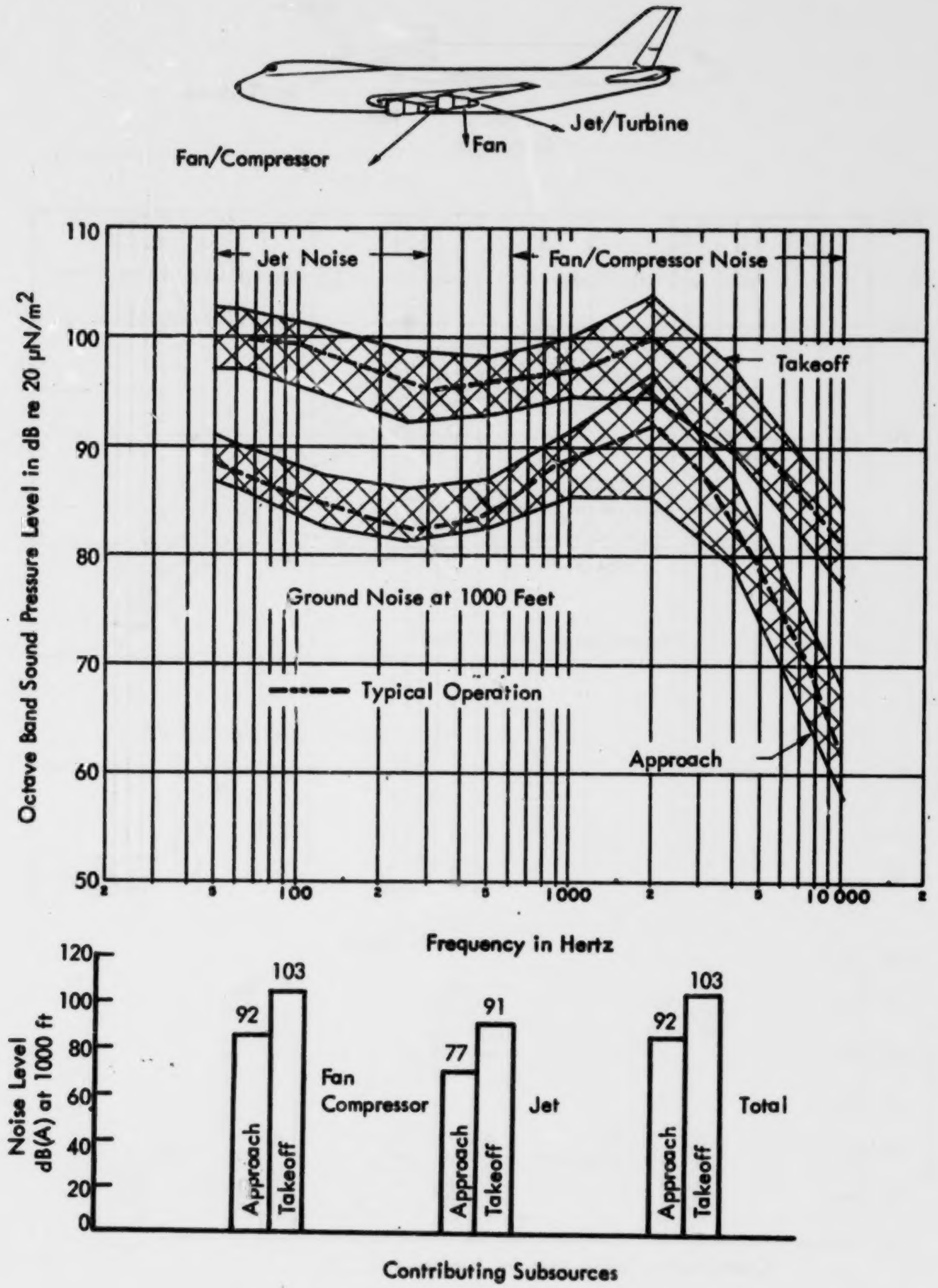


Figure 2.1-4. Noise Levels and Spectra of 4-Engine High Bypass Ratio Turbofan Aircraft

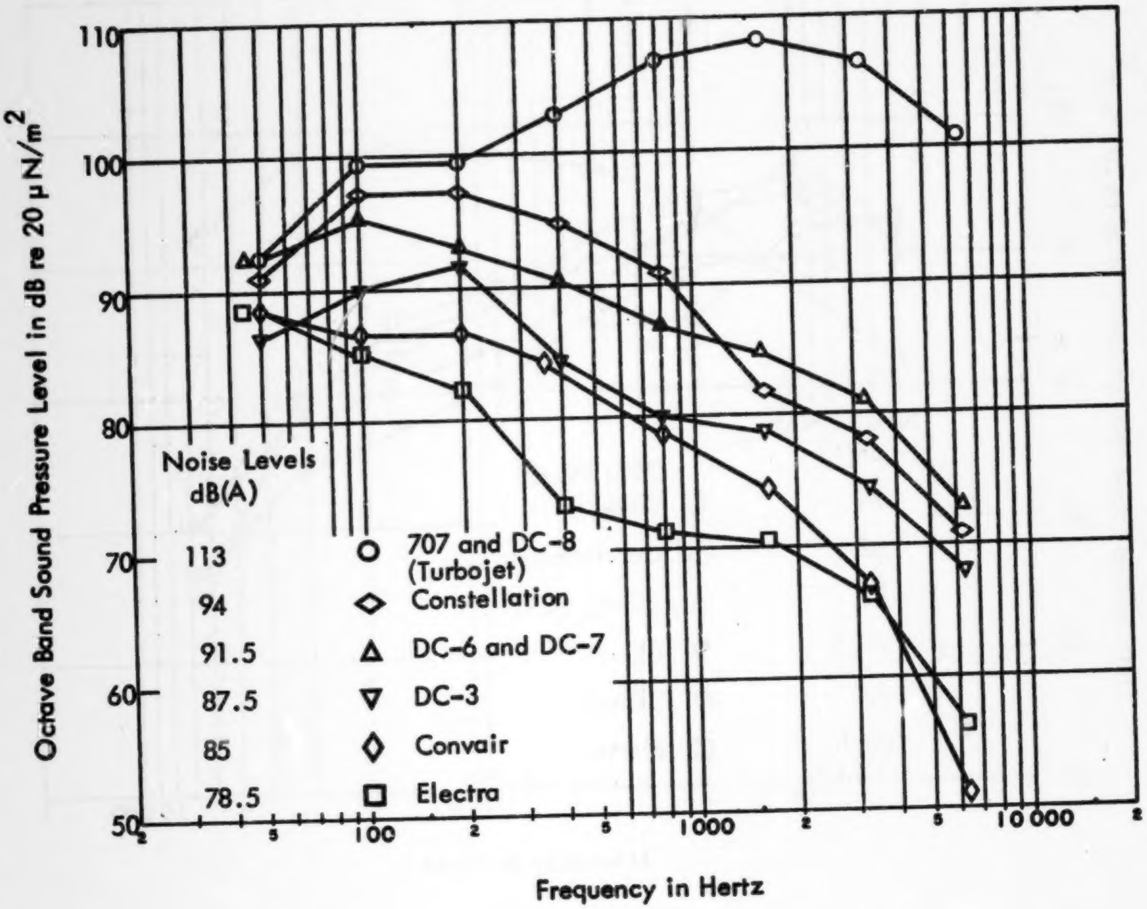


Figure 2.1-5. Mean Noise Level Spectra for Various Types of Aircraft at Approximately 1000 ft Altitude During Takeoff

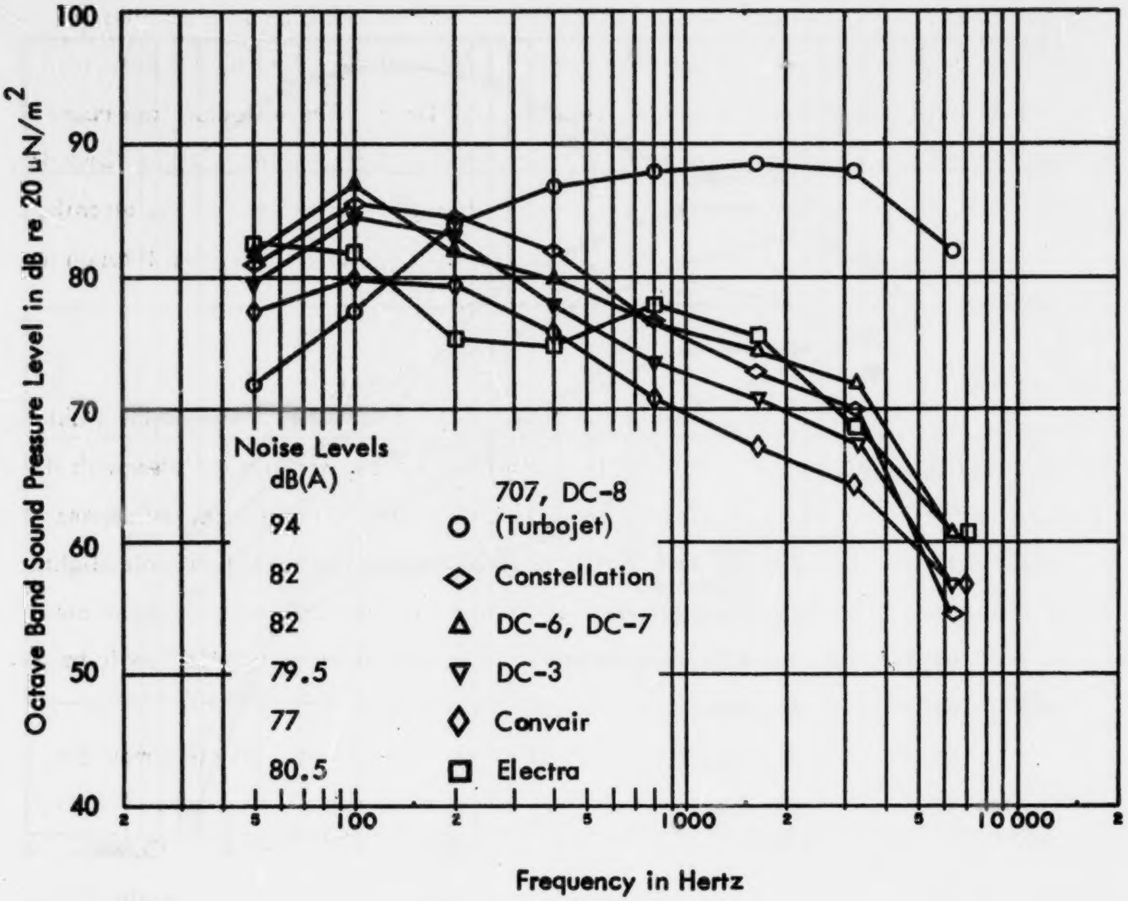


Figure 2.1-6. Mean Noise Level Spectra for Various Types of Aircraft at Approximately 1000 ft Altitude, During Landing

the detailed discussion of propeller noise will be deferred to the General Aviation Category for which it forms the dominant characteristic noise.

The noise level in the interior of jet aircraft is dominated by a different noise source. Because these aircraft travel at high speeds, the pressure fluctuations generated by the turbulent mixing that occurs in the boundary layer between the aircraft fuselage and the surrounding air become significant. These fluctuations cause the fuselage walls to vibrate and radiate noise into the aircraft interior. The "boundary layer" noise dominates at most interior locations except at the aft end of the aircraft, at which low frequency jet noise impinging on the fuselage and transmitted through to the interior may becomes the dominant noise source.[10-13]

Sonic Boom

Supersonic aircraft introduce a new element into the aircraft noise problem. Whereas the noise from subsonic aircraft is primarily a phenomenon associated with the airport environment, the sonic boom generated by aircraft flying at supersonic speeds creates a ground impact underneath its entire flight path. Although supersonic flights by military aircraft over populated and areas within the United States have been prohibited, supersonic military aircraft continue to produce an estimated 6000 sonic booms annually over sparsely populated areas.[15]

When an airplane flies at supersonic speed, it compresses the surrounding air, pushing a shock wave, much like a boat creates a spreading bow wave. This bow wave, or cone of increased air pressure, spreads out behind the airplane. Corresponding waves are generated at locations of airflow discontinuities along the length of the airplane. At great distances, the separate waves or shocks interact with each other and coalesce into two waves, a bow shock and a tail shock. In this form the pressure signature is called an N wave. Figure 2.1-7 shows that as the distance from the airplane is increased, the distance between the bow and tail wave is also increased.[16] The intensity of the sonic boom depends on such factors as speed, altitude, weighted shape of the airplane, atmospheric conditions, and type of terrain over which the aircraft is passing.

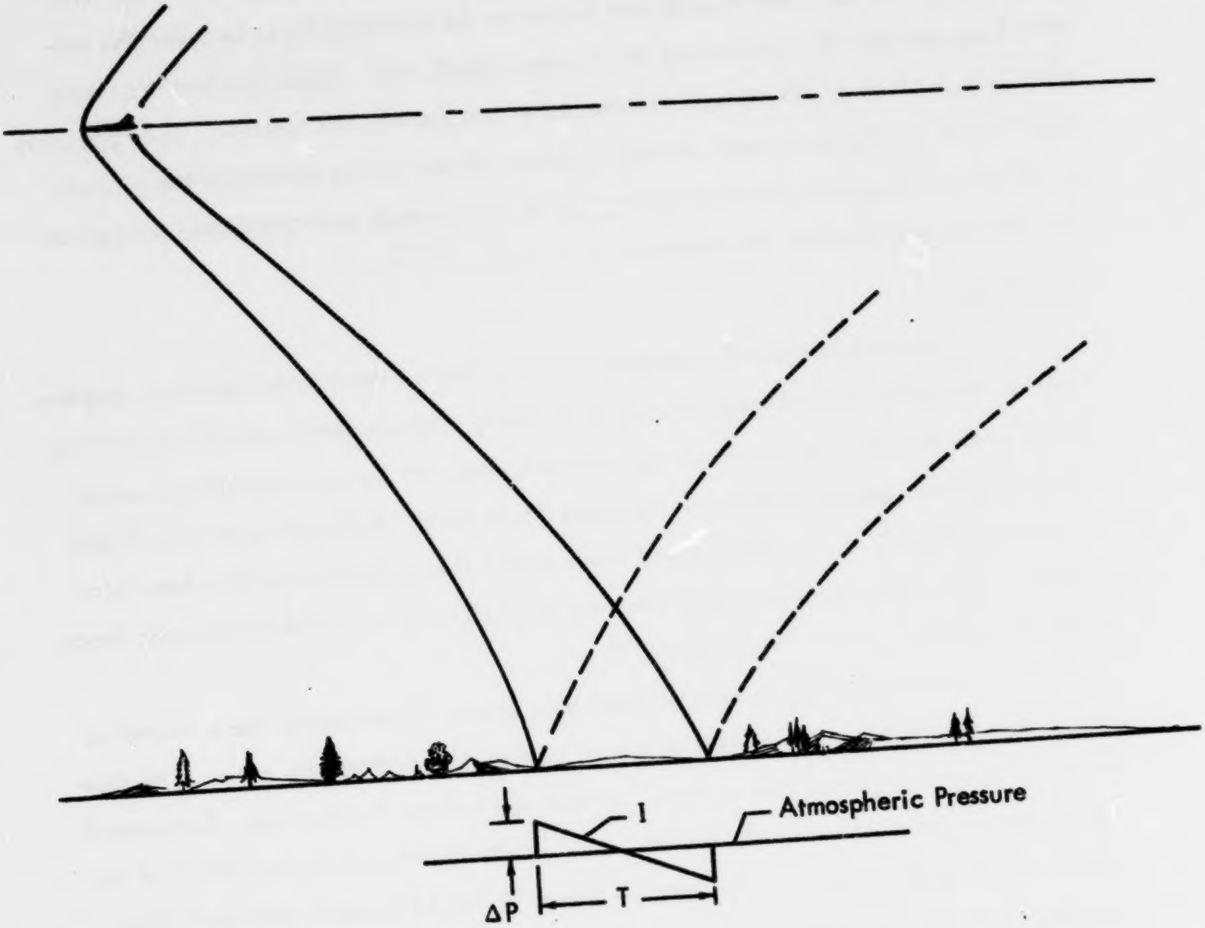

I
Atmospheric Pressure
ΔP
T

Figure 2.1-7. Nature of the Sonic Boom Phenomenon

Community impact studies conducted in anticipation of the United States supersonic transport aircraft have suggested that the sonic booms generated by a fleet of this aircraft would produce a clearly unacceptable noise impact on populated areas. For example, sonic booms generated by the military B-58 aircraft, at a strength of 1.7 pounds per square foot nominal peak overpressure, were judged by residents of a suburban community to be equal in acceptability to the noise from a subsonic jet at about 107 dB(A), which is clearly an unacceptable value.[17] This result, together with the vigorous complaints, political and legal actions encountered in other sonic boom overflights, has led to an administrative decision at the Federal level to prohibit supersonic military and commercial flights over populated areas. This prohibition in the United States, and similar prohibitions in other countries, are expected to continue until new technology developments result in supersonic aircraft concepts that produce acceptably low sonic boom levels.

2.1.3 Environmental Noise Characteristics

The noise generated by commercial aircraft results in two types of noise environments that differ in terms of the noise levels and duration of exposure, as well as in the aircraft operations that generate the noise impact. The participant, or passenger, is exposed to moderately high noise levels throughout the entire history of aircraft operations from the time of boarding the aircraft, takeoff, cruise to the flight destination, and landing. Figure 2.1-8 gives time histories of typical cabin noise levels for the flight duration.[14] If the aircraft makes intermediate stops, the passenger may be subject to this set of operations several times during a single flight.

Commercial jet aircraft are designed to maintain interior noise levels during cruise operations which enable passengers to converse at normal voice with good speech intelligibility. As is shown in Figure 2.1-9, the cruise interior noise levels range typically from 79 to 88 dB(A), depending on the interior location, with a characteristic value of 82 dB(A).[9-13] During takeoff and landing operations, the noise levels in aircraft with wing mounted engines are up to 12 dB higher, but only for periods of up to 1 minute during each operation. The statistical characteristics of the passenger environment, summarized in Table 2.1-1, refer to 1970 figures.[1,2]

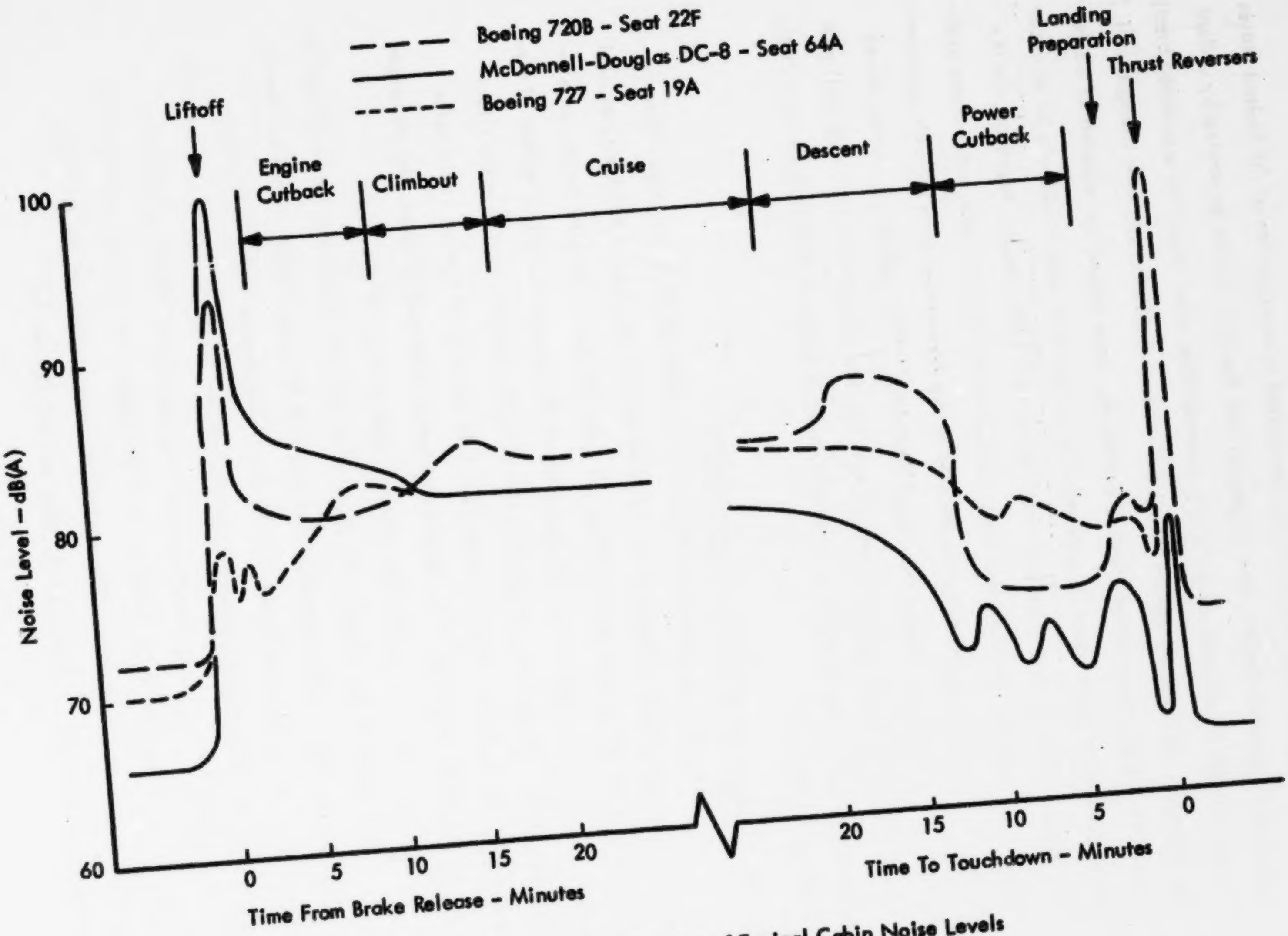


Figure 2.1-8. Time Histories of Typical Cabin Noise Levels

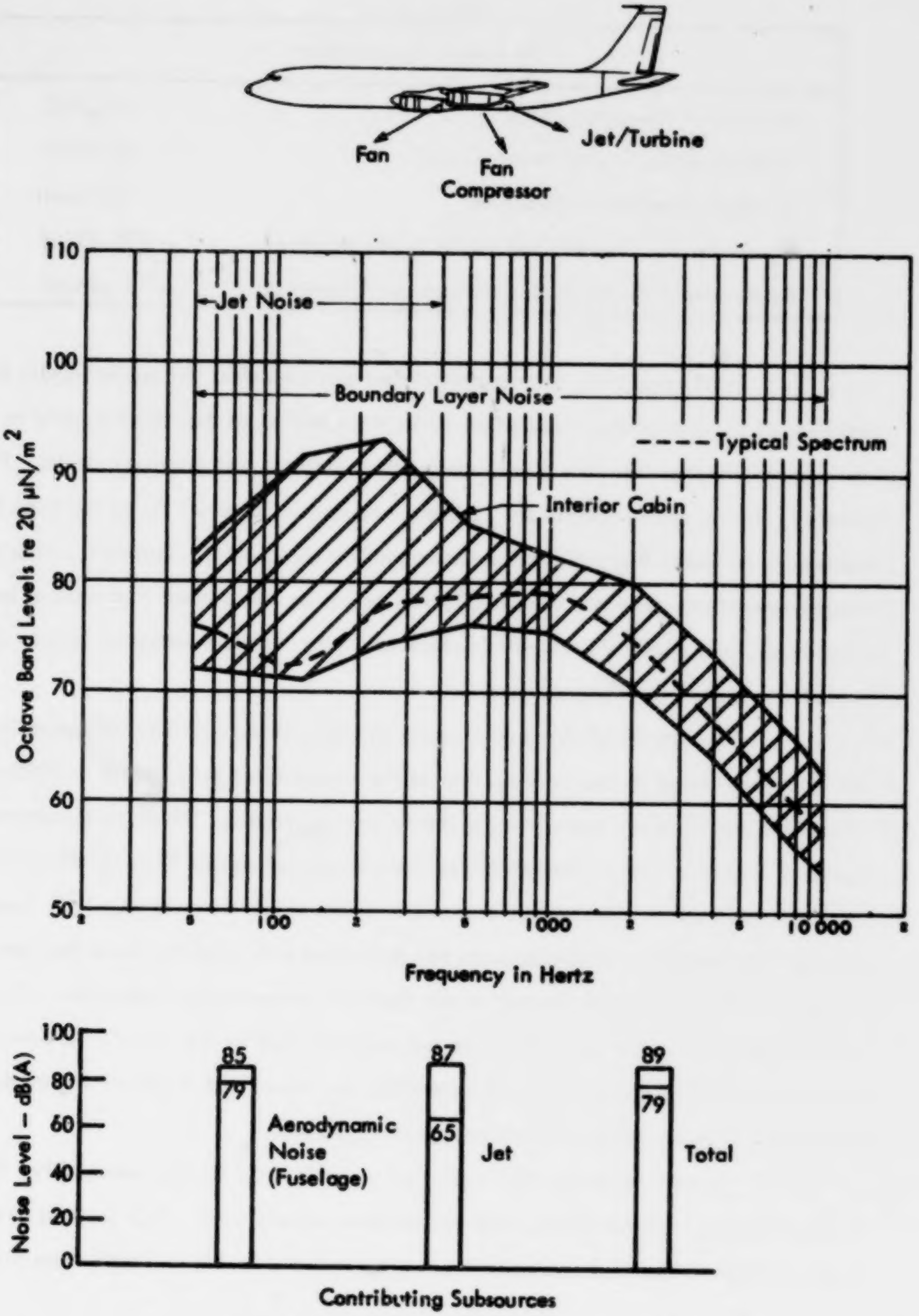


Figure 2.1-9. Interior Cabin Noise Levels and Spectra for Commercial Jet Aircraft

Table 2.1-1

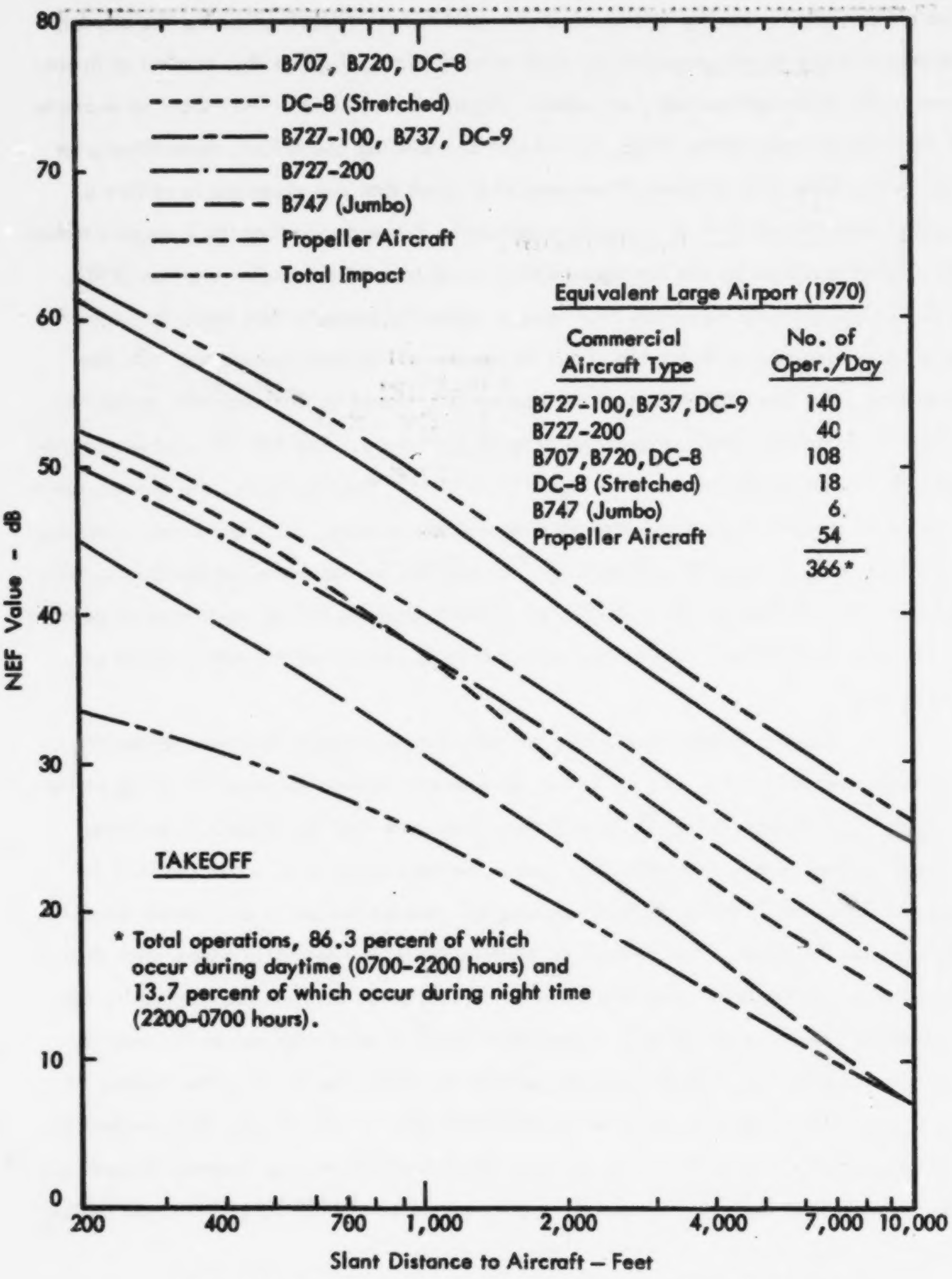
Passenger Environment	
Number of Passengers/Day	– 465,000
Characteristic Cruise Noise Level	– 82 dB(A)
Average Duration of Exposure	– 1.4 hours
Characteristic Takeoff and Landing Noise Level	– ≤ 95 dB(A)
Approximate Duration of Exposure per Operation	– ≤ 1 minute

With respect to the nonparticipant environment, the noise impact from commercial air operations is experienced in the vicinity of the airports, and to a lesser extent further from the airport under the climbout and approach paths. Fortunately, during cruise operations, current commercial aircraft fly at too high an altitude to generate a significant noise impact on the ground. However, takeoff and landing operations generate very high noise levels on the ground that extend over large areas, and where the airport is close to a city, large numbers of people may live within the noise impacted areas.

The growth of the noise impact due to commercial aircraft operations is very closely related to the introduction of the commercial jet aircraft in 1958 and the manner of growth of air travel during the following decade. First, as illustrated in Figures 2.1-5 and 2.1-6, the jet aircraft were approximately 12 to 20 dB noisier on approach and takeoff than piston-engined aircraft which they replaced.[14] Secondly, although the number of major airports has increased only slightly since the late 1950's, the number of commercial aircraft in the fleet has grown many times over. Finally, vast new residential communities have been established in the vicinity of nearly all busy airports. This combination of expanding air travel and residential growth has resulted in a serious airport-community noise problem.

In order to assess the impact of aircraft noise on the community, the Noise Exposure Forecast (NEF) method has been widely used. This method gives a single number rating of the cumulative noise produced in the vicinity of an airport by aircraft operations, taking into account the total mix of aircraft utilizing the airport, subjective noise levels generated by each aircraft class, flight paths, number of operations in day and night periods, et cetera. Figures 2.1-10 and 2.1-11 show an example of NEF values versus slant range, for takeoff and landing operations, respectively, for the various types and numbers of commercial aircraft that are expected to utilize a typical large airport.[1,2] It is readily apparent in this example that the 4-engine turbofan aircraft powered by the first-generation low bypass ratio turbofan engines (B707, B720, DC-8) give the maximum NEF values, primarily because they have the highest noise levels together with having about 30 percent of the total operations. On the other hand, the low NEF values of the Boeing 747, shown in this example, primarily reflect its relatively small percentage of total operations. The NEF 30 contours resulting from this example are shown in Figure 2.1-12.[7,8] For simplicity, the aircraft are assumed to operate in the same direction on a single runway, and the contour combines the effects of both takeoffs and landings. Operations by the 4-engine low bypass ratio turbofan aircraft (Boeing 707 and 720, McDonnell-Douglas DC-8) contribute 69 percent of the total impact area, despite comprising only 30 percent of the total number of operations.

Current Federal guidelines for planning recommend that new residential construction should not be undertaken in areas around airports exposed to values of the NEF rating of 30 and higher.[18] In addition, they state that individuals in existing private residences may complain about noise, perhaps vigorously, when the NEF is between 30 and 40. When the NEF exceeds 40, residential use is considered incompatible with the noise. The community reaction scale[18] essentially agrees with this expected complaint level when the outdoor residual noise level in the community may be classified as urban residential, a condition which is generally met in the vicinity of our major airports. However, if the outdoor residual noise level in the community has a lower value, such as would be expected for quiet or normal suburban residential, it is suggested that the NEF values for equivalent reaction must be lowered accordingly.[18] However, for simplicity in this report, a constant value of NEF 30 will be used for the

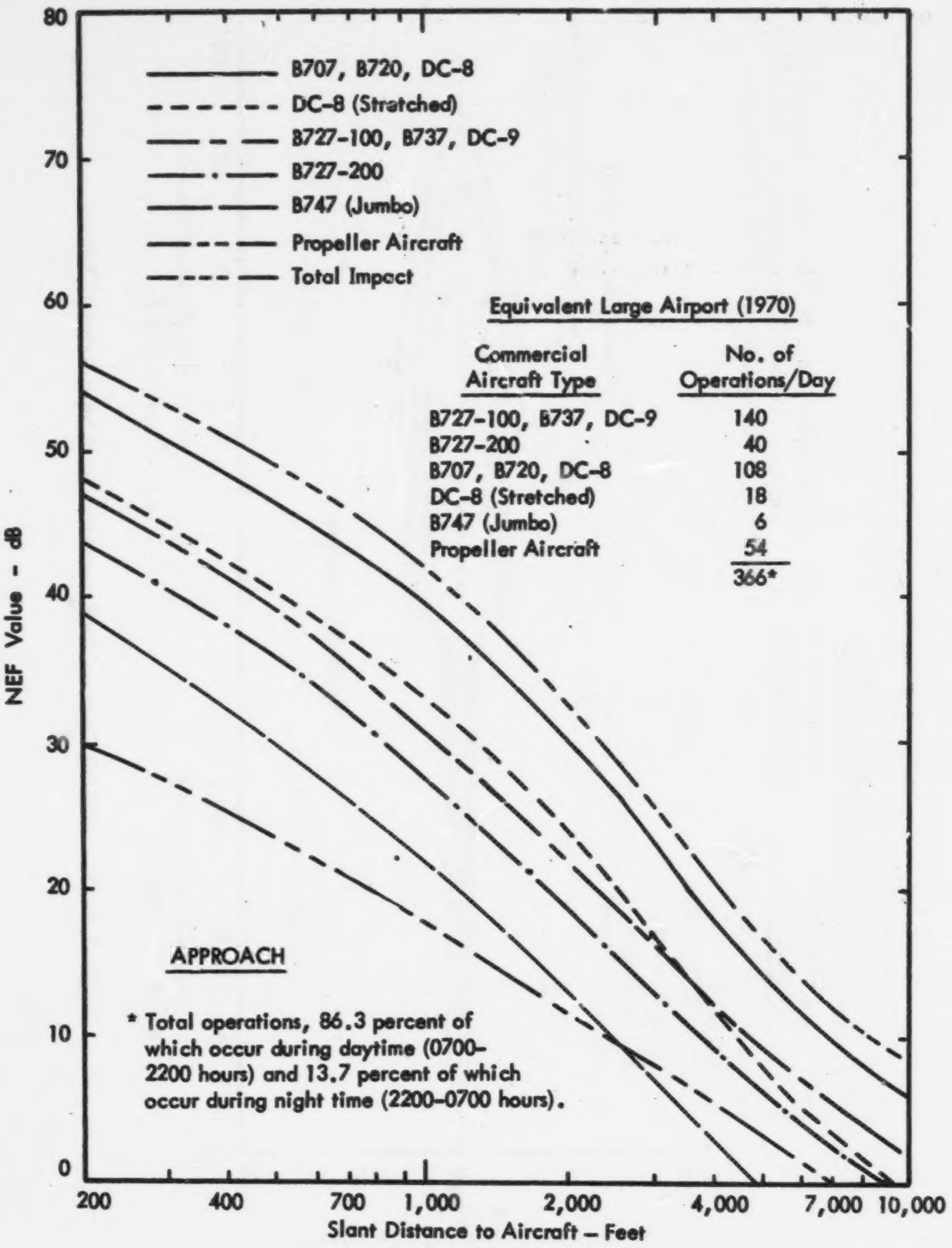


Equivalent Large Airport (1970)

Commercial Aircraft Type	No. of Oper./Day
B727-100, B737, DC-9	140
B727-200	40
B707, B720, DC-8	108
DC-8 (Stretched)	18
B747 (Jumbo)	6
Propeller Aircraft	54
	366*

* Total operations, 86.3 percent of which occur during daytime (0700-2200 hours) and 13.7 percent of which occur during night time (2200-0700 hours).

Figure 2.1-10. Noise Exposure Forecast vs Slant Range (Takeoff) for an Equivalent Large Airport



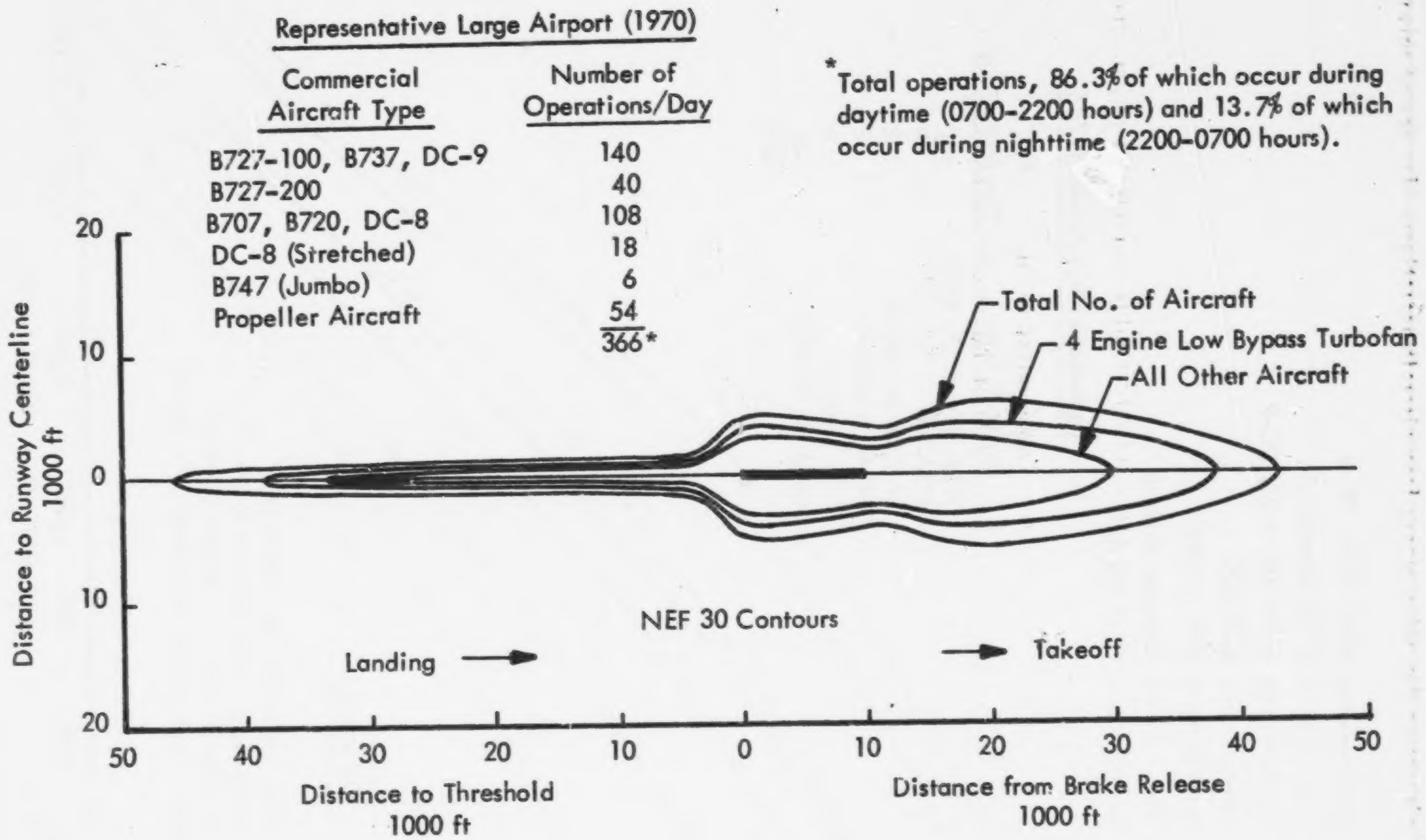
Equivalent Large Airport (1970)

Commercial Aircraft Type	No. of Operations/Day
B727-100, B737, DC-9	140
B727-200	40
B707, B720, DC-8	108
DC-8 (Stretched)	18
B747 (Jumbo)	6
Propeller Aircraft	54
	366*

APPROACH

* Total operations, 86.3 percent of which occur during daytime (0700–2200 hours) and 13.7 percent of which occur during night time (2200–0700 hours).

Figure 2.1-11. Noise Exposure Forecast vs Slant Range (Approach) for an Equivalent Large Airport



Representative Large Airport (1970)

Commercial Aircraft Type	Number of Operations/Day
B727-100, B737, DC-9	140
B727-200	40
B707, B720, DC-8	108
DC-8 (Stretched)	18
B747 (Jumbo)	6
Propeller Aircraft	54
	366*

*Total operations, 86.3% of which occur during daytime (0700-2200 hours) and 13.7% of which occur during nighttime (2200-0700 hours).

Figure 2.1-12. NEF 30 Contours for Representative (Single Runway) Airport

purpose of discussing the noise impact from aircraft operations. The use of this value to define the boundary of the noise impact zone is conservative, but it should not impair any qualitative conclusions, since the majority of the currently impacted area is in the residential urban ambient noise level category.

Within the United States, the total area within which NEF 30 is exceeded has grown from approximately 100 square miles in 1958 to approximately 1450 square miles in 1970.[19,20] These areas are estimated to contain respective populations of approximately 500 thousand and 7.5 million people.[1] A considerably larger number of people are undoubtedly annoyed by aircraft noise, because of the conservatism indicated above, and because over 30 percent of the population exposed to NEF 30 are expected to be very much annoyed with the noise, and approximately 20 percent are very much annoyed when exposed to NEF 20.

2.1.4 Industry Efforts In Noise Reduction

The commercial jet airplane and jet engine manufacturers have generally been involved with the military as well as the civilian aircraft market. In fact, the jet engines that were responsible for ushering in the new era in commercial air transportation were originally developed for military purposes, and the first commercial jet aircraft were based on technology fall-out from the development of large military jet aircraft.

Noise impact has never been a major design constraint in the majority of military applications of jet-powered aircraft. It is not surprising, then, that military jet engines have been, and still are, extremely noisy. The civilian derivatives of these engines have thus had their basic characteristics designed without any noise criteria. Both the airframe and engine manufacturers have been aware of the potential community noise problems due to the excessive noisiness of jet aircraft, and have carried on research and development work on jet engine noise reduction since well before the introduction of the first commercial jet airplanes. Unfortunately, the rapid development of the commercial jet fleet market demanded technological advances in jet engine performance and noise acceptability faster than the embryonic jet engine noise technology was able to accommodate. The first turbojet engines were made moderately quieter by means of jet noise suppressors mounted on the engine tailpipes, but still generated unacceptably high noise levels. The introduction of the low bypass ratio turbofan engines was anticipated to reduce the jet noise problem. However, the appearance of fan noise as a dominant noise source negated some of the expected benefits.

The high bypass ratio turbofan engine represented the first commercial jet engine for which engine noise technology was sufficiently well developed to measurably influence the basic design. Although these engines did not rely on noise considerations as the primary basic design input, they did include the most advanced practical concepts of low noise generation. As will be discussed below, later models of these turbofan engines have incorporated still more noise-reduction features.

Figure 2.1-13 shows the present and a projected composition of the United States commercial jet aircraft fleet.[21] The low bypass ratio turbofan aircraft form the great majority of the fleet and will continue to be dominant until 1985. Hence, the introduction of the quieter high bypass ratio turbofan aircraft will not automatically result in a reduction of the community noise problem except on a long-term basis. This becomes even more apparent on examining the projected growth in commercial aircraft airport operations, presented in Figure 2.1-14. This figure has been prepared on the assumption of a 5 percent annual increase in the number of passenger emplanements and a corresponding annual increase of 3 percent in the number of aircraft operations. The increased number of operations is sufficient to offset the potential benefits of the quieter aircraft unless steps are taken to reduce the noise generation by the older turbofan aircraft.

The commercial jet aircraft industry has been strongly committed to the reduction of jet engine noise, especially so during the last 7 years, and has carried out extensive research and development programs both at industry expense and with the assistance of Federal funding. These efforts have been aimed both at the development of advanced noise technology for use in the design of future jet engines, and the

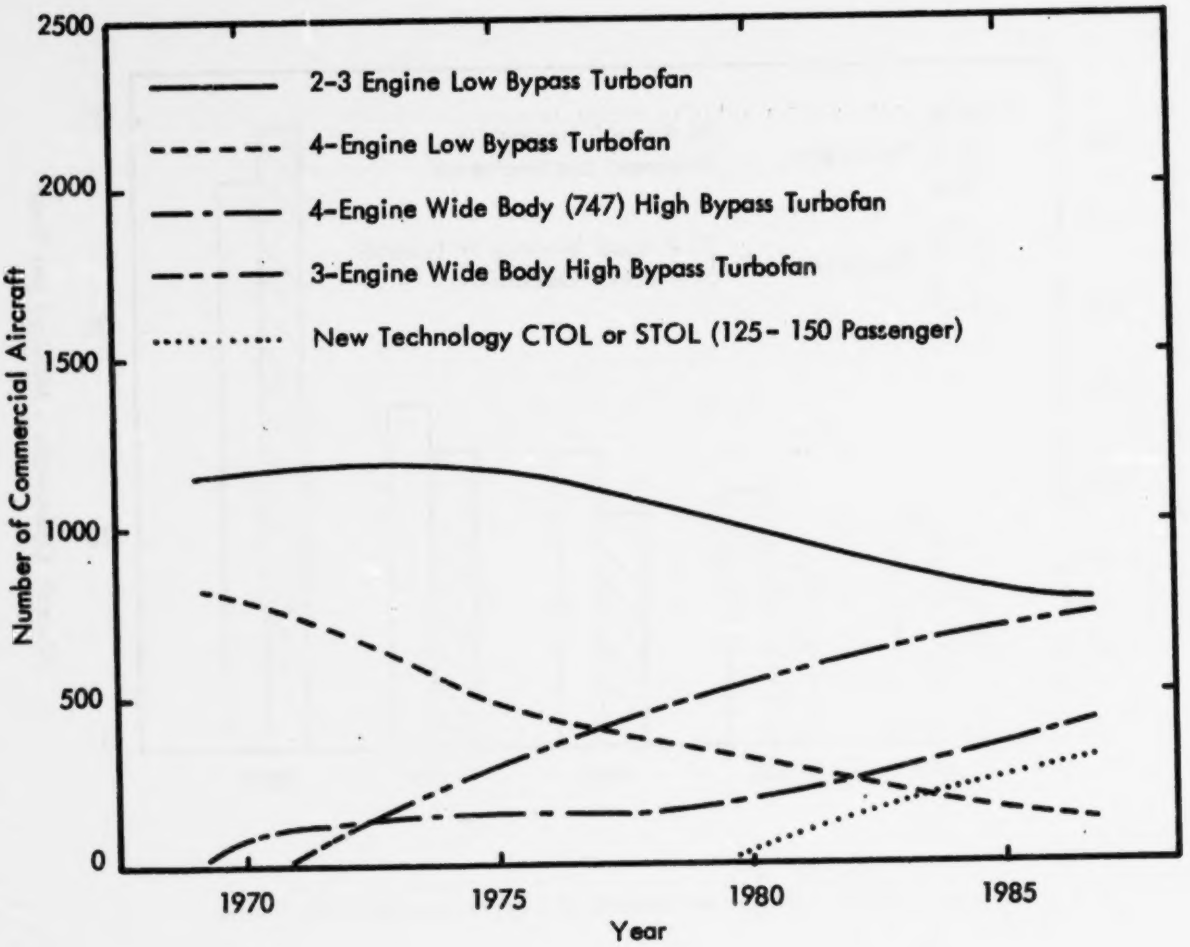


Figure 2.1-13. Projected Change in Commercial Aircraft Fleet Composition (Based on Projected Passenger Capacity Demand Increasing at 5 Percent/Year)

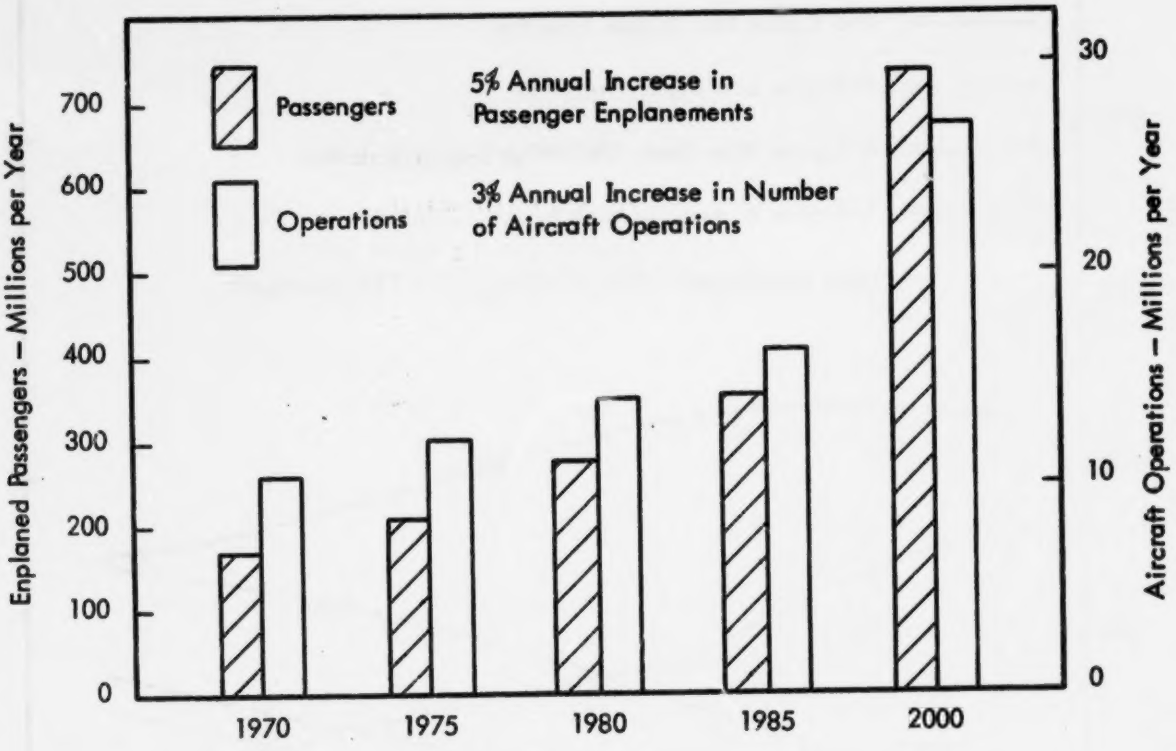


Figure 2.1-14. Projected Growth of Commercial Aircraft Traffic

development of practical concepts and hardware to permit retrofitting of present jet engines. Although these programs have yet not been singularly successful in reducing the noise impact, encouraging progress is being made. The adoption of Federal regulations governing the permissible noise impact by new airplanes and their anticipated extension to cover all commercial aircraft will hopefully spur the implementation of the technology developments in the aircraft fleet. These regulations will be discussed in a separate section below.

The anticipated development of large (125 to 150 passenger) STOL commercial aircraft during the next decade will create new demands on the industry's noise abatement technology. These aircraft will operate out of short field length general aviation and new urban airports as well as the large commercial airports, and must be able to meet stringent noise level standards in order not to impose pollution-level noise impacts at their operation centers. The concept and technology developments planned for these future air transports will be discussed in a later section.

Federal Government Regulations of Aircraft Noise

After receiving authority from Congress, the FAA initiated a lengthy and far-reaching rule-making process which culminated in Federal Aviation Regulation, Part 36 – Noise Standards: Aircraft Type Certification, published in the Federal Register of 21 November 1969.[*] The noise limits of this regulation apply only to subsonic jet aircraft in the following categories:

- Airplanes that have turbofan engines with bypass ratios of 2 or more (i.e., new technology high bypass engines used by the new wide-bodied transport aircraft) and for which application for certification was or is made on or after January 1, 1967.

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[*] The technical requirements of FAR-36 are reproduced in Appendix A.

- For new airplanes that have turbofan engines with bypass ratios of 2 or more, which do not meet FAR-36 noise levels and where application for certification was made prior to January 1, 1967, the FAA will place a time period in the type certificate. At the expiration of this time period, the type certification will be subject to suspension unless the type design of aircraft produced under that type certificate after the end of this time period is modified to comply with the noise limits.
- Airplanes that do not have turbofan engines with bypass ratios of 2 or more (i.e., pure jets or low bypass turbofans as found on most current aircraft) and for which application for certification was made after December 1, 1969.

FAR-36 defines noise limits such aircraft must meet at certain locations with respect to the airport runway, shown in Figure 2.1-15.

Three measurement locations are required in certification. They are:

- Landing – 1 nautical mile from threshold, directly under the aircraft path,
- Takeoff – 3.5 nautical miles from brake release, directly under the aircraft path, and
- Sideline – at the location of maximum noise along a line parallel to and at a distance of 0.35 nautical miles from the runway centerline, for aircraft which have four or more engines; and 0.25 nautical miles from the runway centerline, for aircraft which have three or fewer engines.

Additional restrictions are imposed to insure that aircraft become progressively quieter at flight positions further from the airport.

The noise limits at the three measurement positions are given in terms of the aircraft's maximum certificated gross weight. The permissible variation with gross

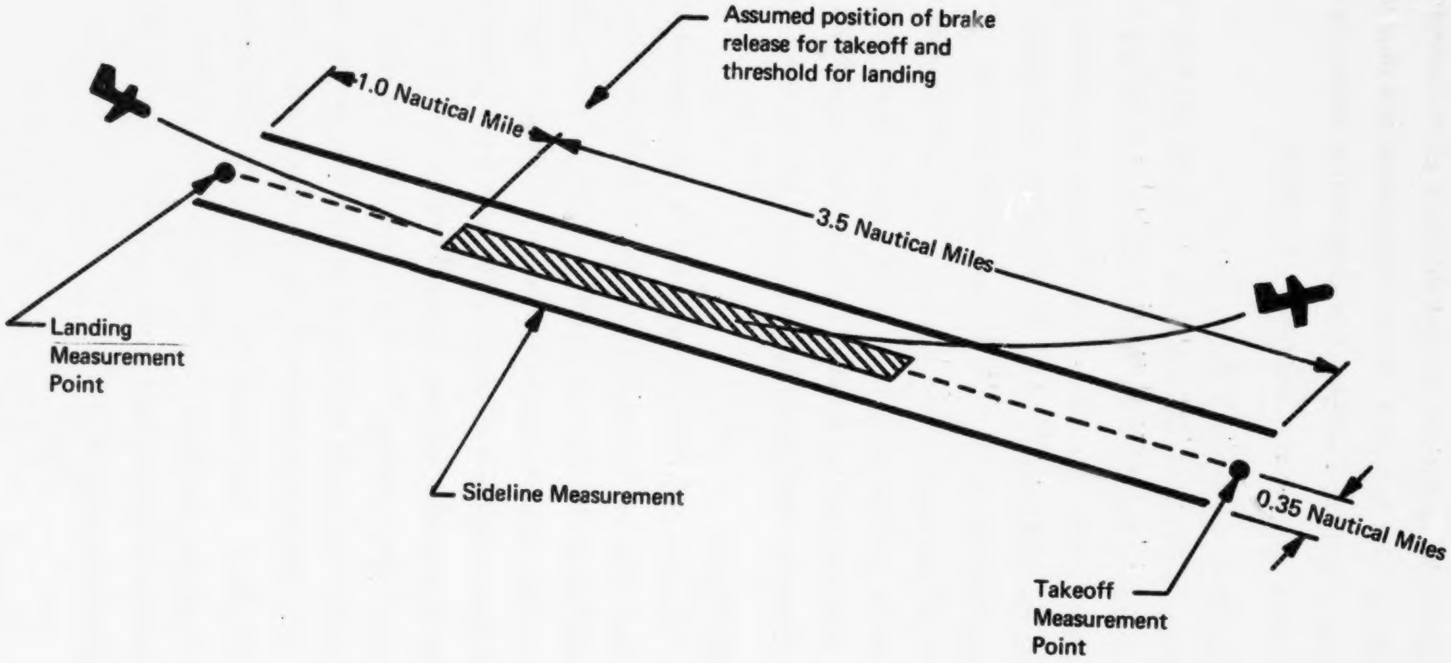

Assumed position of brake release for takeoff and threshold for landing
1.0 Nautical Mile
3.5 Nautical Miles
Landing Measurement Point
Sideline Measurement
0.35 Nautical Miles
Takeoff Measurement Point

Figure 2.1-15. FAR-36 Noise Certification Measurement Positions

weight gives implicit recognition to the fact that for a given technology in engine design, the absolute noise from an airplane must increase with required thrust – which in turn must increase with gross weight. For many airline flights, the aircraft operate at less than maximum gross weight, and hence, less noise.

The Effect of FAR-36 on the Noise of Future Aircraft

Most of the turbofan aircraft which constitute the bulk of the present jet aircraft fleet exceed the FAR-36 noise limits. Figures 2.1-16 to 2.1-18 make these comparisons for the landing, takeoff and sideline noise measurement points, respectively. It is obvious that the noise levels of most current aircraft are significantly higher than the noise limits of FAR-36, particularly for takeoff and landing.

The comparisons show the amount of noise reduction that will be accomplished by designing and producing future aircraft which meet the certification requirements. Effective perceived noise levels of future aircraft will be reduced by as much as 14 EPNdB for takeoff and landing, and 5 EPNdB along the sideline.

Noise Reduction Progress

In the previous section, it was noted that the research efforts by the industry have been directed towards both the development of advanced technology quiet engines and the development of retrofit concepts for current engines. At this time, both efforts have yielded results that are in evidence in new aircraft in the current aircraft fleet. Figure 2.1-19 shows the noise levels generated by the older turbojet and low bypass ratio turbofan engines compared with the new advanced technology high bypass ratio turbofans.[4,5,6] It is noted that the second generation turbofan engines of the older type are up to 8 EPNdB quieter than the first types on the basis of equal thrust. The JT9D high bypass ratio engine is also quieter, despite producing 250 percent more thrust. The newest engine shown, the CF6, generates noise levels up to 16 EPNdB less per unit thrust than the first turbofan engines. This engine represents a significant advancement in the application of noise reduction technology, and will be discussed in more detail.[4]

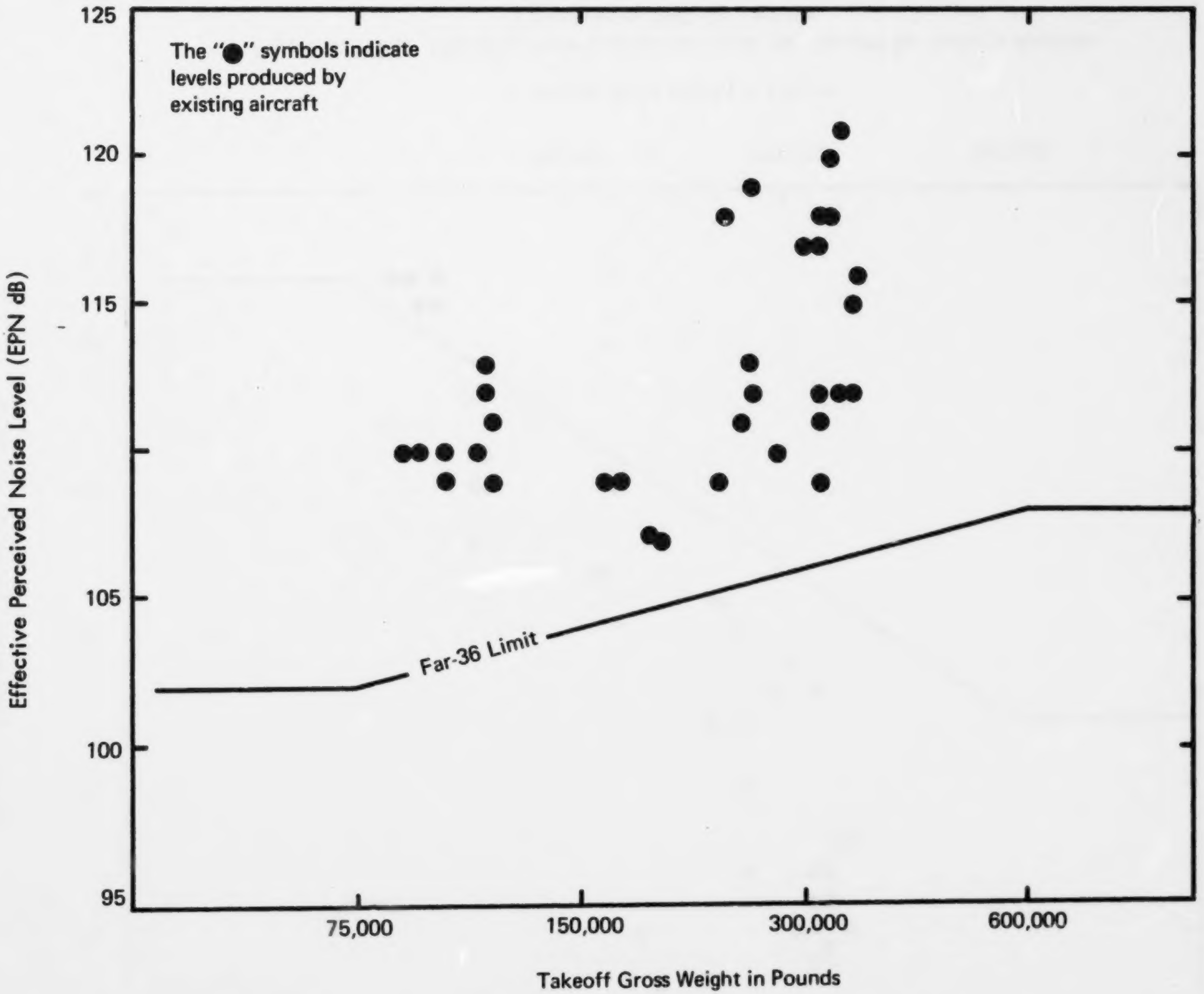


Figure 2.1-16. Effective Perceived Noise Level for Landing for Today's Aircraft Compared to FAR-36 Limits

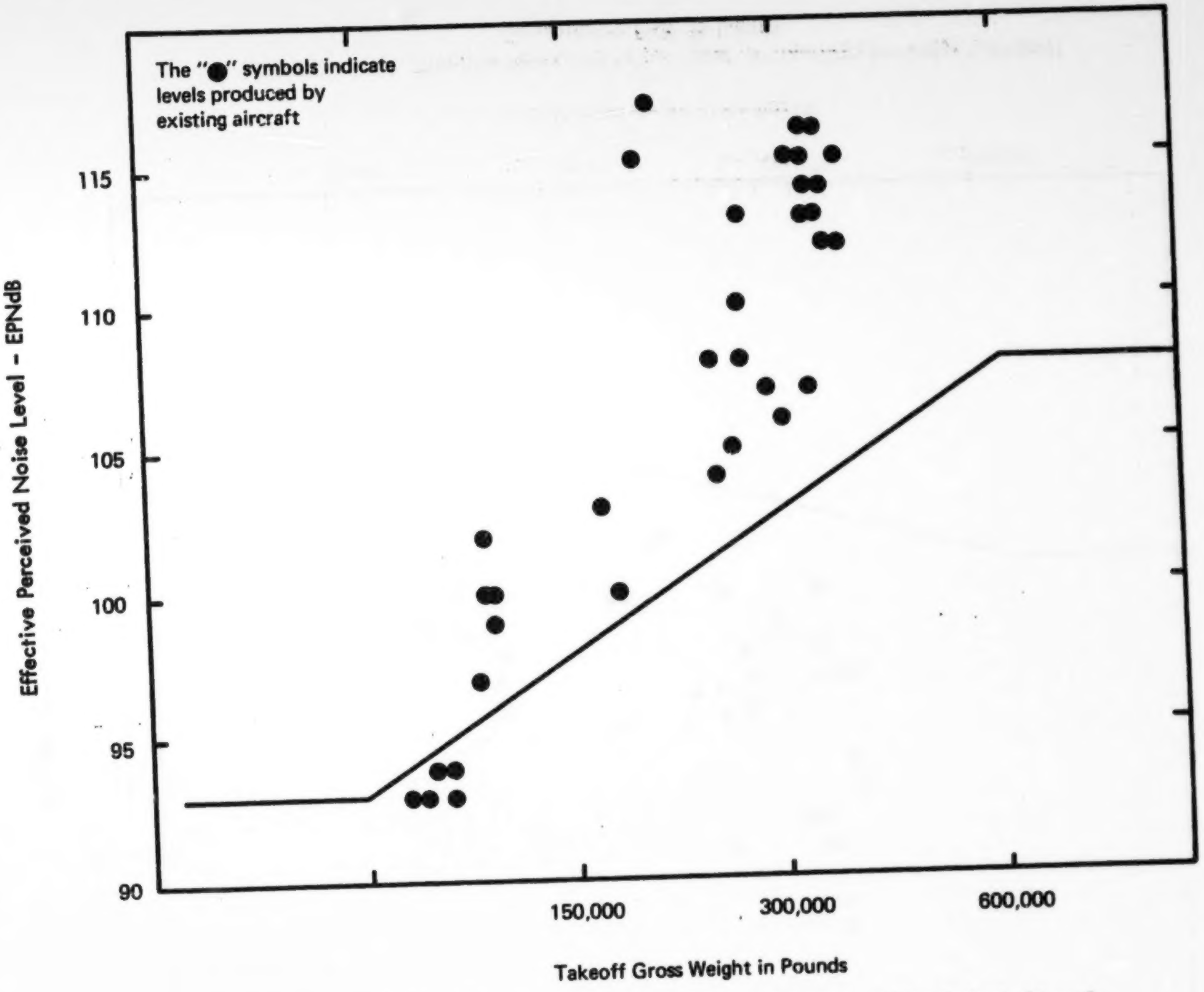


Figure 2.1-17. Effective Perceived Noise Level for Takeoff for Today's Aircraft Compared to FAR-36 Limits

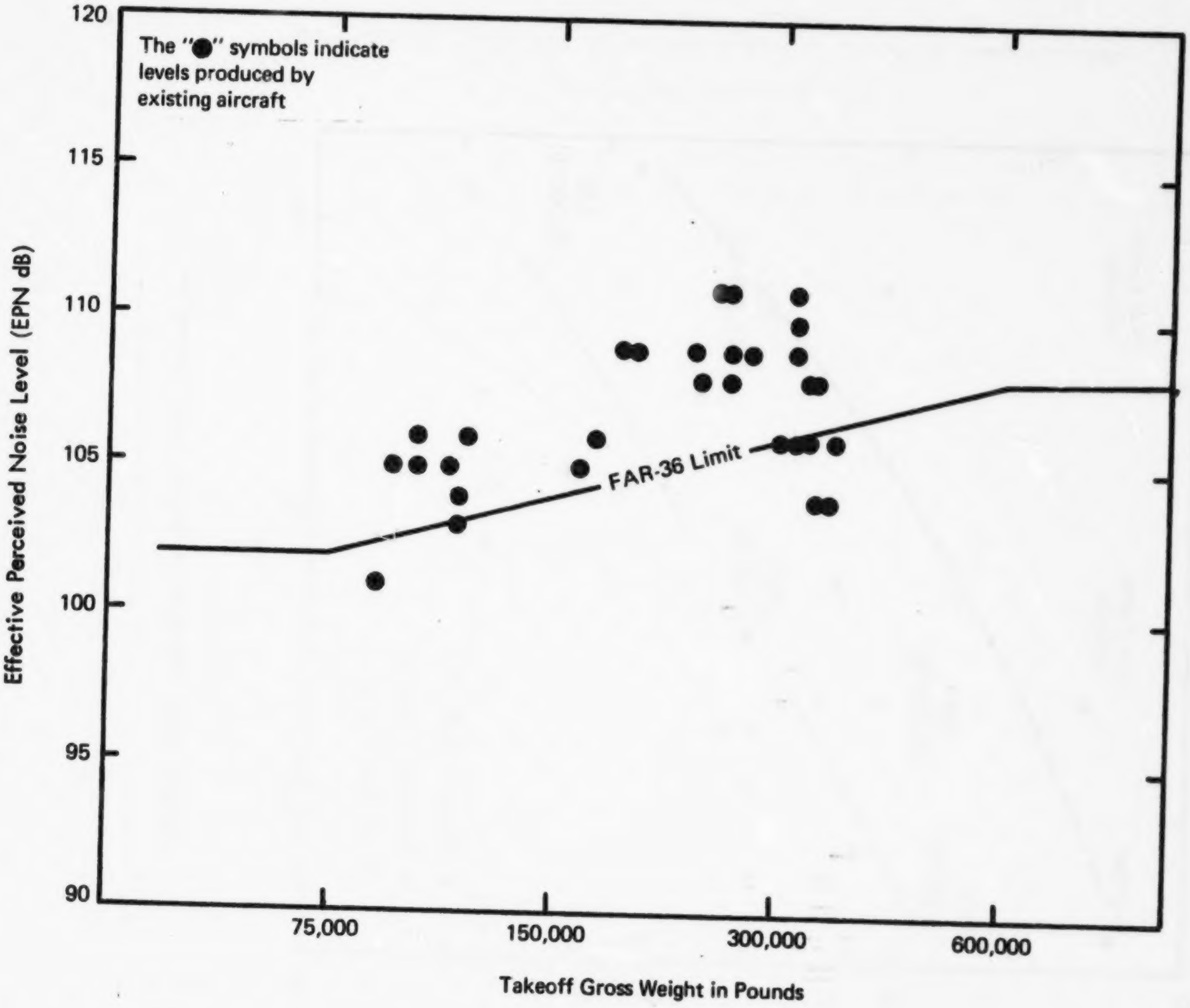


Figure 2.1-18. Effective Perceived Noise Level at Sideline for Today's Aircraft Compared to FAR-36 Limits

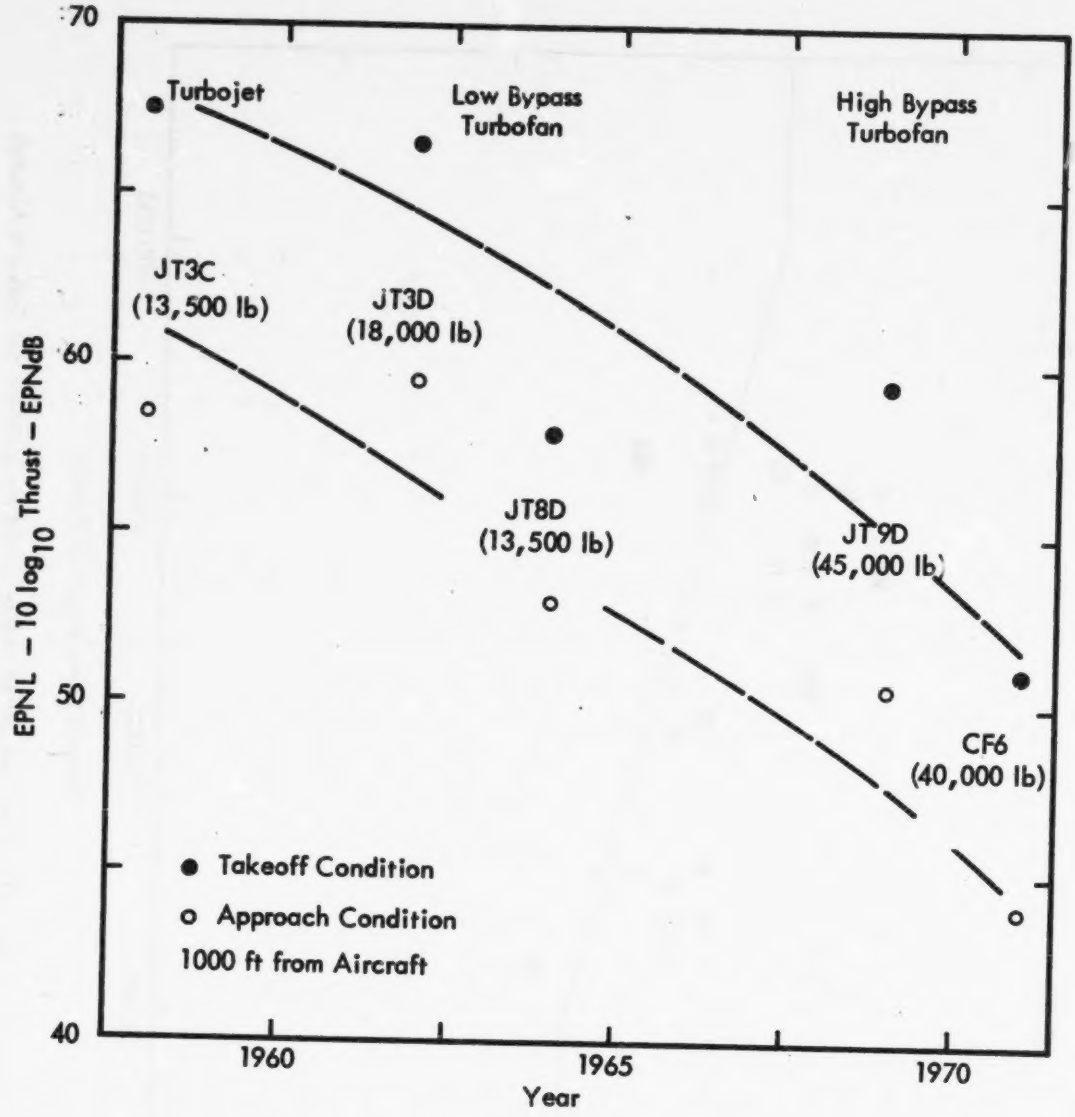


Figure 2.1-19. Trends in Jet Engine Noise Generation

Three basic features of the CF6 engine are dominantly responsible for its low noise characteristics. The first is the selection of high bypass ratio in order to reduce the jet exhaust velocity and hence greatly reduce the jet exhaust noise. The second is the advanced technology design of the fan section to minimize the generation of discrete frequency turbomachinery noise. The third, and perhaps the most significant noise reduction feature, is the use of long inlet and fan discharge ducts that are lined with sound-absorptive treatment in order to reduce the transmission of turbomachinery noise out from the interior of the engine. This combination of features has resulted in noise levels that make the DC-10-10 aircraft, powered by the CF6 engine, much quieter than current aircraft as shown in Table 2.1-2 below:

Table 2.1-2

Maximum Perceived Noise Levels of the DC-10-10 Relative to Those of Current 4-Engine Jet Transport[4]

- Current Jet Transports Powered by Four JT3D-3B Engines
- Relative Levels in PNdB

Takeoff	1000 Feet Outdoors	3500 Feet Indoors
Full Thrust	-11.5	-15
75 Percent Thrust	-13.5	-13
Approach	**400 Feet Outdoors**	**1500 Feet Indoors**
Typical Thrust	-10	-11

Figure 2.1-20 shows the noise spectrum of the DC-10-10 compared with that of a current 4-engine turbofan aircraft. It is apparent that both the jet exhaust noise and the high frequency turbomachinery noise have been significantly reduced.

NASA has funded several research and development programs aimed at developing technology for the retrofit of current turbofan engines. The NASA Acoustically Treated Nacelle Program attempted to reduce the fan noise radiation from the inlet and discharge ducts of 4-engine low bypass ratio turbofan aircraft by treating the nacelle with sound absorbing lining.[22] Independent studies were carried out by both Boeing and McDonnell-Douglas on B707-320B and DC-8-55 aircraft. These programs achieved a significant reduction in approach noise, but only a slight reduction in takeoff and sideline noise. However, the weight and cost penalties involved are too severe to be readily accepted by the aircraft operators. The main results of the programs are summarized below in Table 2.1-3.

Table 2.1-3

NASA Acoustically Treated Nacelle Program[21]

Variable	Boeing	McDonnell-Douglas
Reduction of Approach Path Noise (3° approach at 1 n.mi.)	15.5 EPNdB	10.5 EPNdB
Range Effect	200 n.mi. loss	150 n.mi. gain
Weight Penalty	3140 pounds	332 pounds
Cost of Retrofit per Aircraft (300 to 400 aircraft)	$1,000,000	$655,000
Increase in Direct Operating Costs	9.6 percent	4.2 percent

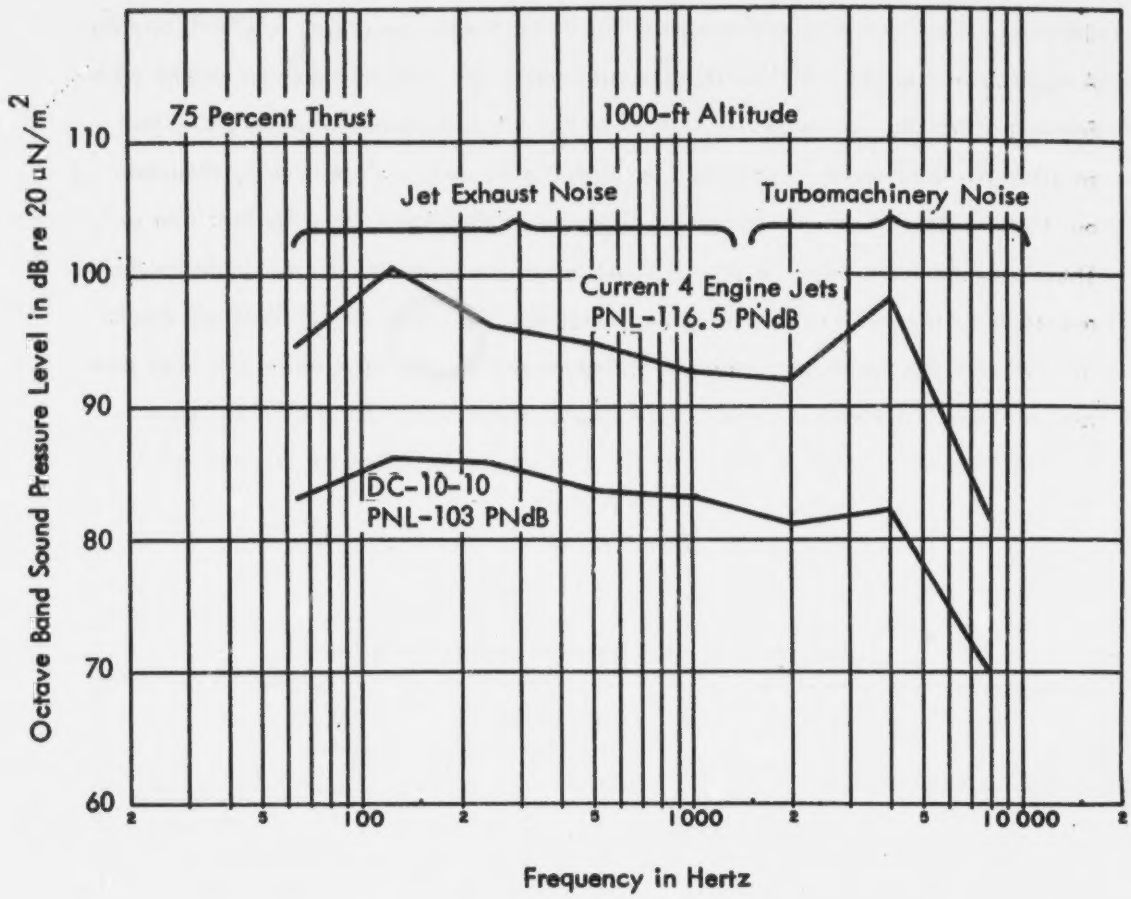


Figure 2.1-20. Flyover Noise Levels – DC-10-10 Compared to Current Jet Transports Powered by (4) JT3D-3B Engines

Another NASA-funded program is aimed at demonstrating the capability of advanced fan design technology and nacelle acoustic treatment to guide the design of a new high bypass ratio turbofan engine with takeoff and approach noise levels significantly lower than have been achieved to date. Carried out by General Electric and Boeing, this Quiet Engine Program is due to be completed during 1973.[23] Integration studies conducted by McDonnell-Douglas show that substitution of an engine with the design parameters of the Quiet Engine for the old turbofan engines on DC-8 and B707 aircraft would result in improved performance as well as dramatically reduced noise levels.[24] However, the high cost of engine replacement, and the fact that only experimental component hardware will come out of the program, throws doubt on the prospects of its immediate implementation. Rather, the Quiet Engine Program should be viewed as a development of new technology which can be applied in design of new engines for future aircraft. The expected results of the Quiet Engine Program are summarized below in Table 2.1-4, with the CF6 engine included for comparison:

Table 2.1-4

NASA Quiet Engine Program

Noise Level Goals Compared with B707/DC-8[22]			
Flight Condition	Noise Reduction – EPNdB at FAA Measurement Positions		
	Bare Quiet Engine	Acoustically Treated Quiet Engine	CF6 Engine (DC-10)
Takeoff	13	23	18
Approach	17.5	25.5	11.5

An alternative approach to noise reduction for the current fleet of aircraft is that of altering flight procedures. At some airports, the concept of reduced thrust takeoff has been adopted. This procedure consists of a full thrust takeoff and initial climb, after which the aircraft climbs over heavily populated areas at a reduced thrust for some distance before resuming a normal climb. By this method, maximum noise reductions at the FAA takeoff measurement position of 6 to 10 EPNdB may be expected for 2- to 3-engine low bypass ratio turbofan aircraft and 3 to 6 EPNdB for 4-engine low bypass ratio turbofan aircraft.[25] For new aircraft incorporating the CF6 engine technology, thrust reduction does not appreciably change the noise levels.[4] Additional fan noise suppression will be necessary to realize the potential of this operational procedure for these advanced technology engines.

In order to reduce the noise impact during approach, a "two-segment" landing procedure has been proposed. This consists of an initial approach glide slope of 6 degrees down to a yet unspecified distance from the end of the runway, at which the standard 3 degree approach is resumed. In analytical studies carried out by NASA, reduction of 10 PNdB or more was achieved at 1.5 nautical miles from the runway threshold for profiles with an intercept altitude of 400 feet.[26,27] Figure 2.1-21 illustrates this procedure for a current 4-engine turbofan aircraft and shows the effect of retrofit with the NASA Acoustically Treated Nacelle concept.[28] However, it must be realized that feasibility of the steep approach in terms of airplane operational safety has not been verified. This factor must be thoroughly evaluated and assessed before a decision on the adoption of this landing procedure can be made.

Plans for Future Suppression of Noise

The commercial jet transport industry, together with several Federal agencies, is expected to continue and in some areas intensify its research and development programs aimed at achieving quieter air transportation systems. These programs include the development of practical and economical retrofit hardware, research into quiet engine technology beyond the scope of the Quiet Engine Program, and the development of STOL transportation concepts.

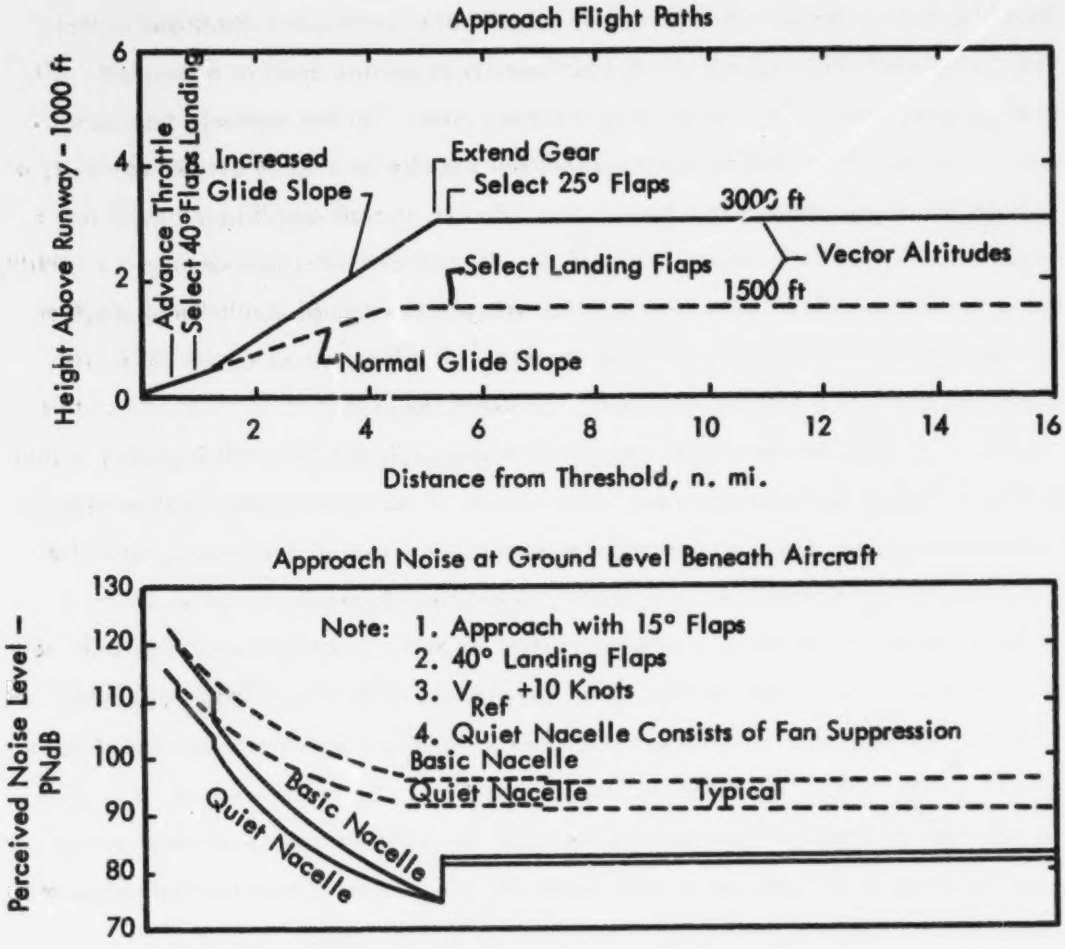


Figure 2.1-21. Effects of Flight Procedure Changes on Noise Reduction for the Case of a 4-Engine Turbofan Aircraft

On the basis of the technology developments resulting from the NASA Acoustically Lined Nacelle Program, FAA is funding a development program to design and manufacture noise reduction packages suitable for retrofitting the current low bypass ratio turbofan engines.[29] The possible future implementation of these retrofit packages in the aircraft fleet will insure compliance with the FAA noise regulations.

NASA is funding several preliminary studies to determine the feasibility of a future advanced technology transport aircraft. Three separate noise objectives are being considered: the current FAA noise regulations (FAR-36), FAR-36 minus 10 PNdB, and FAR-36 minus 20 PNdB. NASA anticipates a 6 to 10 year development program for this aircraft, starting in the middle 1970's.[30] The future development of short-range V/STOL transportation systems is discussed fully in the V/STOL section of this report. However, the potential large jet-powered STOL aircraft falls logically within the scope of commercial jet transportation. NASA is currently funding preliminary development of STOL jet propulsion systems, and has proposed the development of a 150 passenger STOL airplane, with the concurrent development of a quiet STOL jet engine. These developments include a primary emphasis on noise reduction, with the planned requirement of a maximum noise level of 95 PNdB at a distance of 500 feet from the aircraft. The 3-year prototype STOL program is currently scheduled for completion at the end of 1975.[30,31]

Table 2.1-5 summarizes some of the major Federally-funded technology development programs that are exclusively oriented toward jet engine noise reduction or include noise reductions as a primary requirement (anticipated future programs included).

2.1.5 Noise Reduction Potential

The potential noise reduction achievable by means of current and potentially available technology, starting with the technology demonstrated in the CF6 engines and those of the Federally-funded research programs, is summarized in Table 2.1-6.[4,23] The noise levels are specified in terms of the FAR-36 takeoff measurement position.

Table 2.1-5

Federal Noise Abatement Programs[22,29,30,32]

Program	Approximate Program Cost Millions of Dollars	Scheduled Completion Date
NASA Acoustically Lined Nacelle Program	15	1968
NASA Quiet Engine Program	22	1973
DOT Retrofit Program	7-15	1973
STOL Noise Reduction Demonstrator Program	8	1972
Augmentor Wing STOL Program	1.5	1972
STOL Prototype Program	100	1975
STOL Quiet Engine Program	58	1975
Advanced Technology Program	250	1983

Table 2.1-6

Estimated Aircraft Noise Reduction Potential for Takeoff

EPNdB at FAA Measurement Position			
	Jet Noise EPNdB	Fan and Core Noise Reduction dB re DC-10-10	Total EPNdB
DC-10-10 Technology	95	0	100
Quiet Engine	94	-10	95
Quiet Engine with Optimum Jet Noise Technology	88	-10	91
Further Fan and Core Noise Reduction: Optimum Quiet Engine	88	-16	89

This analysis suggests that a noise reduction of 11 EPNdB below the noise levels generated by the DC-10-10 aircraft is possible. It must be realized, however, that a high level of investment by Federal Agencies and the aircraft industry in research and development will be necessary to achieve this goal, particularly in the area of core noise reduction.

The requirement of 95 PNdB at 500 feet for the 150-passenger STOL transport must be examined in order to assess whether this noise level is attainable with current potential jet engine technology. Application of the optimum Quiet Engine concept discussed above results in a noise level 5 to 10 PNdB higher than the objective. It must be realized, however, that the STOL aircraft will have a somewhat lower critical requirement for cruise efficiency than do conventional jet aircraft. Hence, the STOL power plant may incorporate a sonic inlet to further reduce forward radiated fan noise and a geared fan concept that permits still higher bypass ratios with resulting lower jet velocity. The combined effect of these features may be sufficient to gain the extra noise reduction, but there may be unavoidable performance penalties associated with the requirement.

The potential noise reduction discussed above will be examined in light of the future requirements. In attempting to establish specific noise reduction objectives for the commercial jet aircraft fleet, it is instructive to consider the growth of the noise impact during the last decade due to commercial aircraft operations, and attempt to predict future trends on the basis of current and potential jet engine noise reduction technology. Obviously, the projected rate of growth of commercial air traffic will influence these estimates. Extrapolating from the traffic growth during the 1960's and predicting the impact of the anticipated social and economic changes during the next decades, FAA and others have arrived at projected annual rates of growth of up to 12 percent.[33,34] Recent estimates by the commercial aircraft industry on the future commercial aircraft market, however, are consistent with an annual growth rate of 5 percent.[21] The latter figure, although realistic from the point of view of the growth in population and gross national product, is sufficiently low that it may be considered a conservative estimate, or a lower bound.

Figure 2.1-22 shows the growth in noise-impacted areas since the introduction of commercial jet aircraft, and projects the future trend in noise impact on the assumption of a 3 percent annual growth in the total number of aircraft operations, corresponding to the 5 percent annual growth in the number of passenger emplanements discussed above.[19] The use of this constant ratio assumes that the current trend toward increased aircraft capacity will continue, and may well cause an underestimate of the growth of operations beyond 1985 if the trend does not continue.

The following factors were considered in the calculation of the noise-impacted areas:

- Airport land, surrounding industrial land, and other compatible land are included in the total noise-impacted areas. The airport land above is estimated to cover 250 square miles in 1970, and this figure may increase in the future.
- The growth of air freight is not sufficient to become a controlling factor.
- A 5 dB reduction in the NEF value was assumed to give a 55 percent reduction in area.
- The constant mix of daytime-nighttime operation remains unaltered.
- No change in aircraft aerodynamic performance or flight procedures.
- The trends in the growth or decrease of the impacted areas are considered to be reasonably accurate. The expected accuracy of the actual values, however, are probably only with ±50 percent.
- NEF 30 was used to define the impact boundary. This is a relatively high noise exposure criterion, particularily for suburban communities. Therefore the areas represent minimum estimates of impact.

Figure 2.1-22 shows a great range in the projected impact area depending on the application of noise reduction technology to the future commercial aircraft fleet. As an extreme example, maintaining the current aircraft noise levels would result in an increase in impacted areas to 185 percent of the 1970 figure by the year 2000.

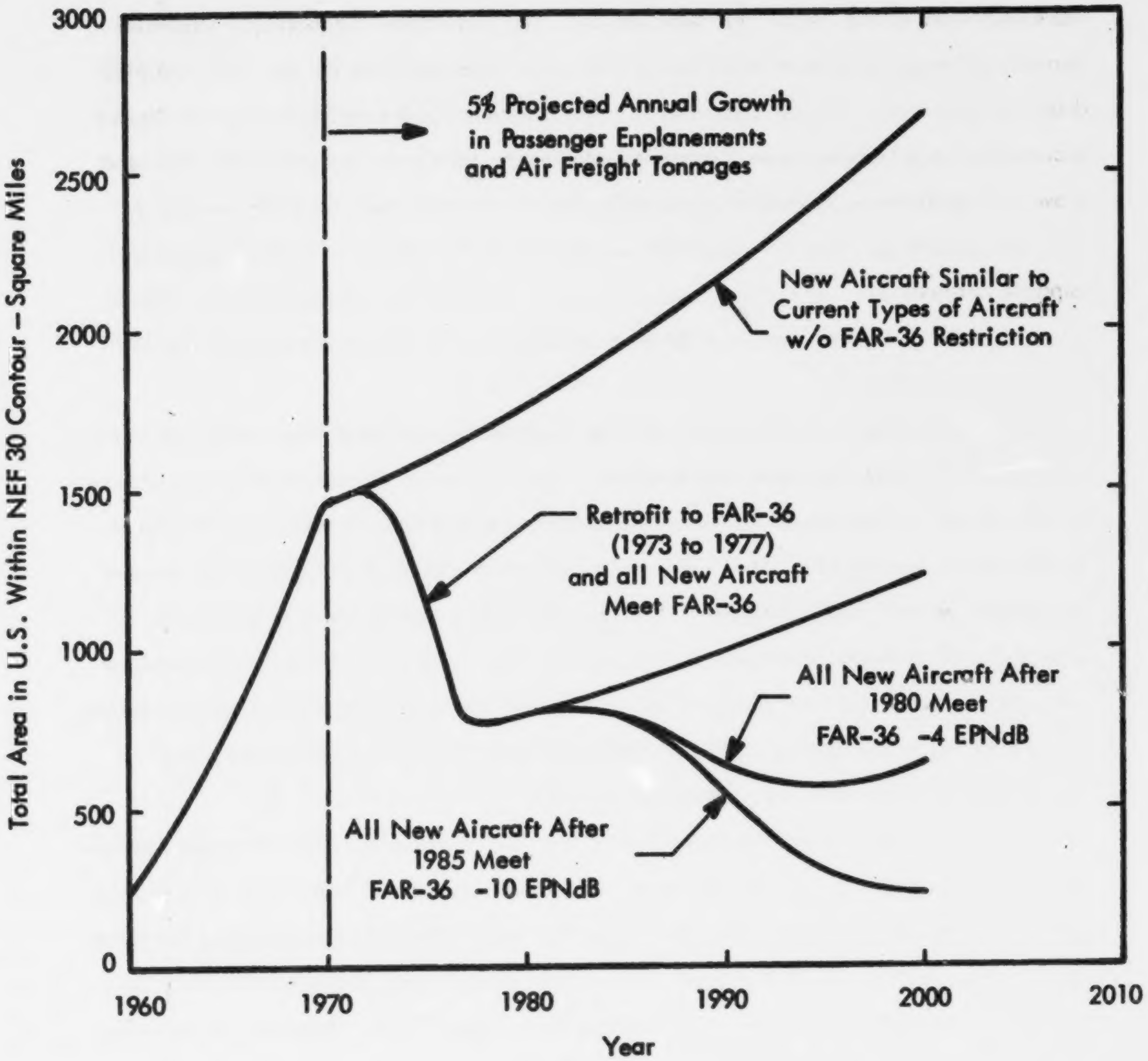


Figure 2.1-22. Estimated Noise-Impacted Areas (30 NEF or Higher) as Function of Jet Engine Noise Reduction Goals

The application of retrofit to the existing aircraft fleet to ensure that all commercial aircraft comply with FAR-36 criteria would result in a significant initial decrease in impact area in the 1976-1987 time period. This significant decrease demonstrates the effectiveness of aircraft certification for noise accomplished by the FAA, coupled with the significant 10+ dB reduction in noise between 1958 and 1968 accomplished by government and industry research and development. However, by year 2000 the land area will again have increased measurably due to the projected increased number of aircraft operations. The two additional curves show the effects of further reduction in aircraft noise levels. The attainment of aircraft noise levels corresponding to FAR-36 minus 10 EPNdB would result in a 83 percent reduction in impact area below the 1970 value by year 2000.

In order to further illustrate the implications of these noise reduction values, Figure 2.1-23 shows the dependence of the respective noise impact areas on the choice of the annual rate of growth in aircraft operations, assuming a constant rate of growth in the period from 1970 to 2000. The noise reduction effect of changes in operational procedures has also been included. The lower bound in impact area for which this effect may be considered reflects the assumption that these procedures may be applied only above certain critical aircraft altitudes during the takeoff and approach operations, corresponding to a ground distance of 8000 feet from threshold on approach, and 12,000 feet from aircraft rotation on takeoff.[25-28]

The philosophy may be adopted that the tremendous growth in noise impact since 1960 has been due to the fact that commercial jet aircraft have been excessively noisy, and hence, the noise reduction objectives should be aimed at reducing the noise impact areas to the pre-1960 values. This criterion may seem somewhat arbitrary in view of the considerable expansion in airport areas since 1960. However, it includes consideration of the fact that whereas the NEF 30 contour lies outside the most vigorous complaint area for urban residents, it still has a considerable annoyance associated with its noise levels (more than 30 percent of the populace registers annoyance), and it is in the vigorous complaint area for quiet suburban areas.[18]

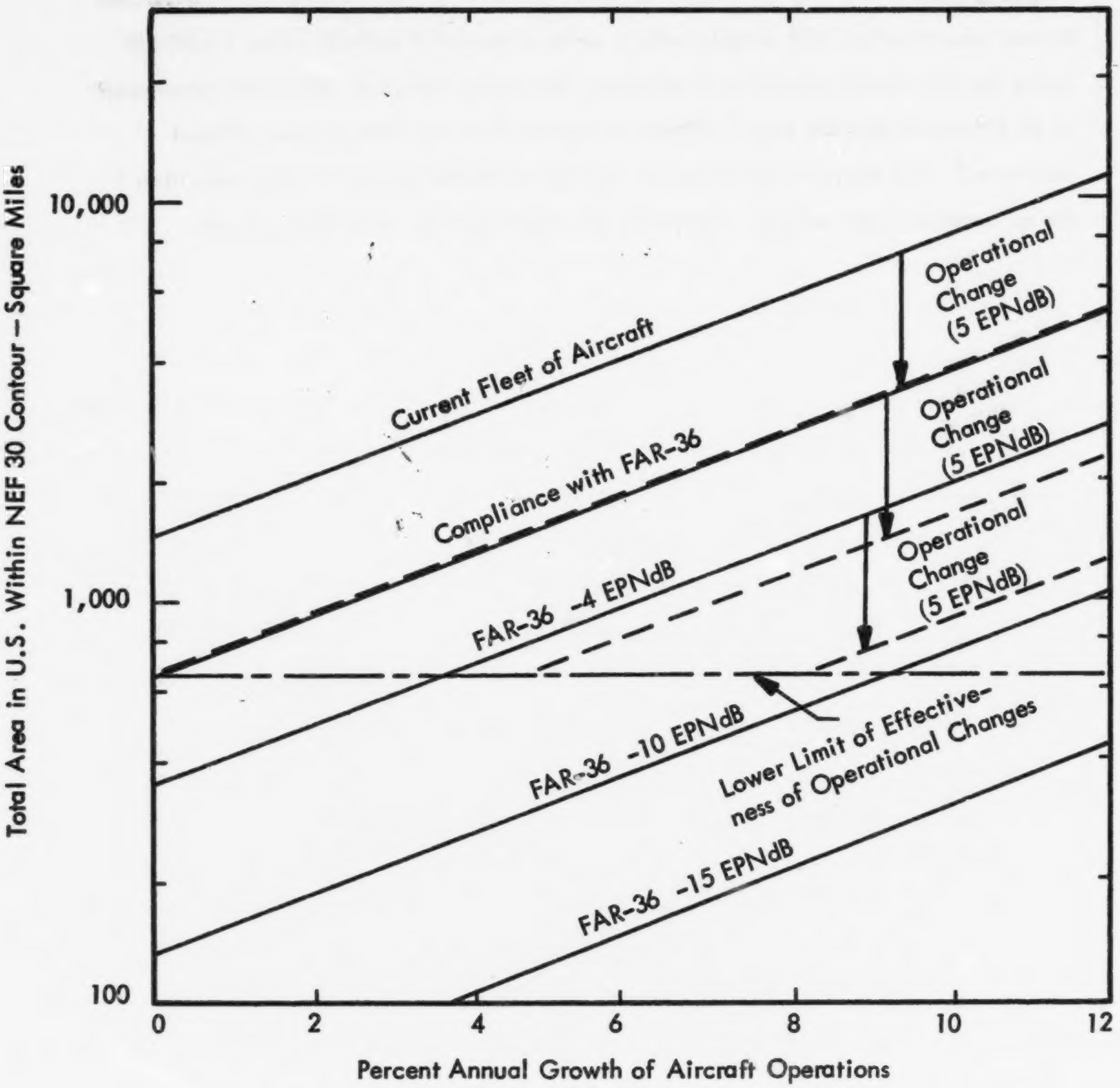


Figure 2.1-23. Noise-Impacted Areas (30 NEF or Higher) vs Traffic Growth (Projection for Year 2000)

Referring to Figure 2.1-23, the NEF 30 impact area may be reduced to within its 1960 value of 200 square miles by year 2000, i.e., the airport and surrounding industrial area, for annual aircraft operation growth rates of up to 8 percent if new aircraft after 1985 comply with a noise criterion of FAR-36 minus 15 EPNdB. Using the DC-10-10 aircraft as a baseline, this noise reduction objective corresponds to 89 EPNdB on takeoff and 93 EPNdB on approach at the FAR-36 measurement positions.[4] This takeoff requirement is equivalent to the potential noise reduction for an optimum quiet engine, previously discussed together with Table 2.1-6.

2.2 V/STOL Aviation

2.2.1 Introduction

Although current Vertical/Short Takeoff and Landing (V/STOL) aircraft are inherently part of both the commercial and general aviation fleet, their unique capability of operating from very small airfields or from urban centers tends to distinguish them in terms of noise impact from the remainder of the aviation transportation industry.

The present V/STOL fleet is predominantly comprised of helicopters (VTOL). The STOL fleet is not yet a significant reality, but is currently undergoing considerable Federal and industry study. The principal objective of STOL aircraft is to move much of the inter-city air transportation (short-haul) away from the congested major-hub airports and toward the urban community where the public will be better served. Tentative noise goals have been proposed for aircraft operating from the projected peripheral STOL ports, but as yet a community-compatible noise goal has not been defined for the intra-city heliports now in operation, or for those which will serve as city-feeder terminals for the STOL ports.[1-4]

Figure 2.2-1 shows the typical subcategories of the present V/STOL fleet and their major applications. Of the current total of 3260 vehicles, approximately 1900 are based in counties with population densities in excess of 1000 people per square mile. The most significant increase of usage in recent years has been by civil government agencies, with 120 operator agencies in 1971 compared with 80 in 1969. In particular, the number of city police helicopters is rapidly increasing, with a total of about 150 vehicles in present use.[5,6]

Commercial helicopter service grew until 1967, when a total of 29.7 million revenue-passenger miles were flown. Since 1967 this service has declined to 11.3 million passenger miles for a revenue of $7.6 million in 1970. Cargo traffic has followed the same trends with 34 thousand ton-miles transported in 1970 for a revenue of $350 thousand. Manufacturers shipped approximately 500 completed rotor aircraft in 1970.[7,8]

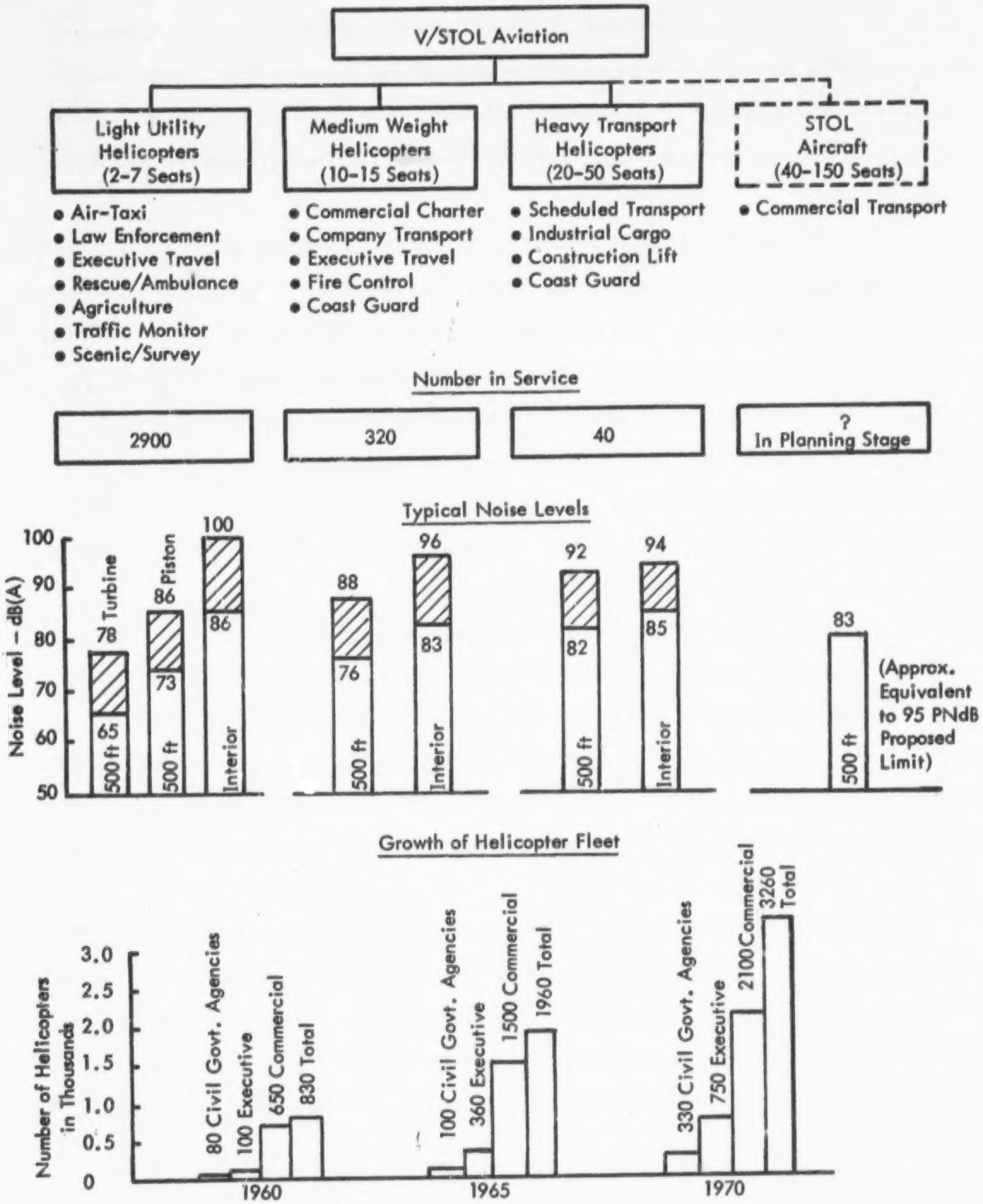


Figure 2.2-1. Characteristics of V/STOL Aircraft

Commercial usages are predominantly charter air-service operations, with only about 15 vehicles on scheduled intra-city air carrier routes. The average route stage length of the latter services is 20 miles, in 10 minutes flight time, compared with a possible 40 minutes (or more) by city road transport. This market potential can be expected to be more fully exploited with the introduction of urban STOL ports. Figure 2.2-2 shows one projection (DOT/NASA, 1971) of the expected 1985 V/STOL fleet.[9]

2.2.2 Source Noise Characteristics

VTOL Aircraft

The helicopter is unique in that its noise signature is characteristically different from all other common noise generators. This difference is attributable to the main (lifting) rotors which rotate at relatively low revolutions per second, but generate very high amplitude pulsating sound pressures at their blade tip regions. The resulting noise, observed both at ground level and within the aircraft cabin, is a distinctive low frequency throbbing sound which often suddenly increases in level and exhibits more of a slapping nature during descent, maneuver, and high-speed cruise operations. Due to the predominance of the low frequency content of the noise, it is extremely difficult to control its intrusion into the passenger cabin or into ground buildings by sound-insulation methods, which are notably inefficient in the low frequency range. This problem is further complicated by the fact that low frequency sound propagates through the atmosphere more efficiently than higher frequencies. Thus, helicopter noise can be distinguished at greater distances than can most other sources of equal noise level. Typical noise spectra for two classes of current commercial helicopters, shown in Figures 2.2-3 and 2.2-4, demonstrate these frequency characteristics.[10-14]

The noisiness value of rotor noise is often under-predicted by current subjectively weighted noise scales such as dB(A) and EPNdB. These scales do not account for the attention-gathering potential of a helicopter, which results from

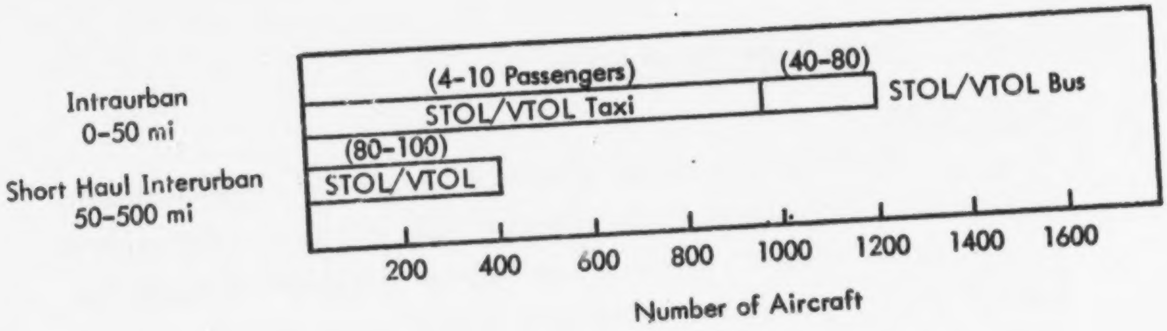


Figure 2.2-2. Potential 1985 U.S. V/STOL Fleet

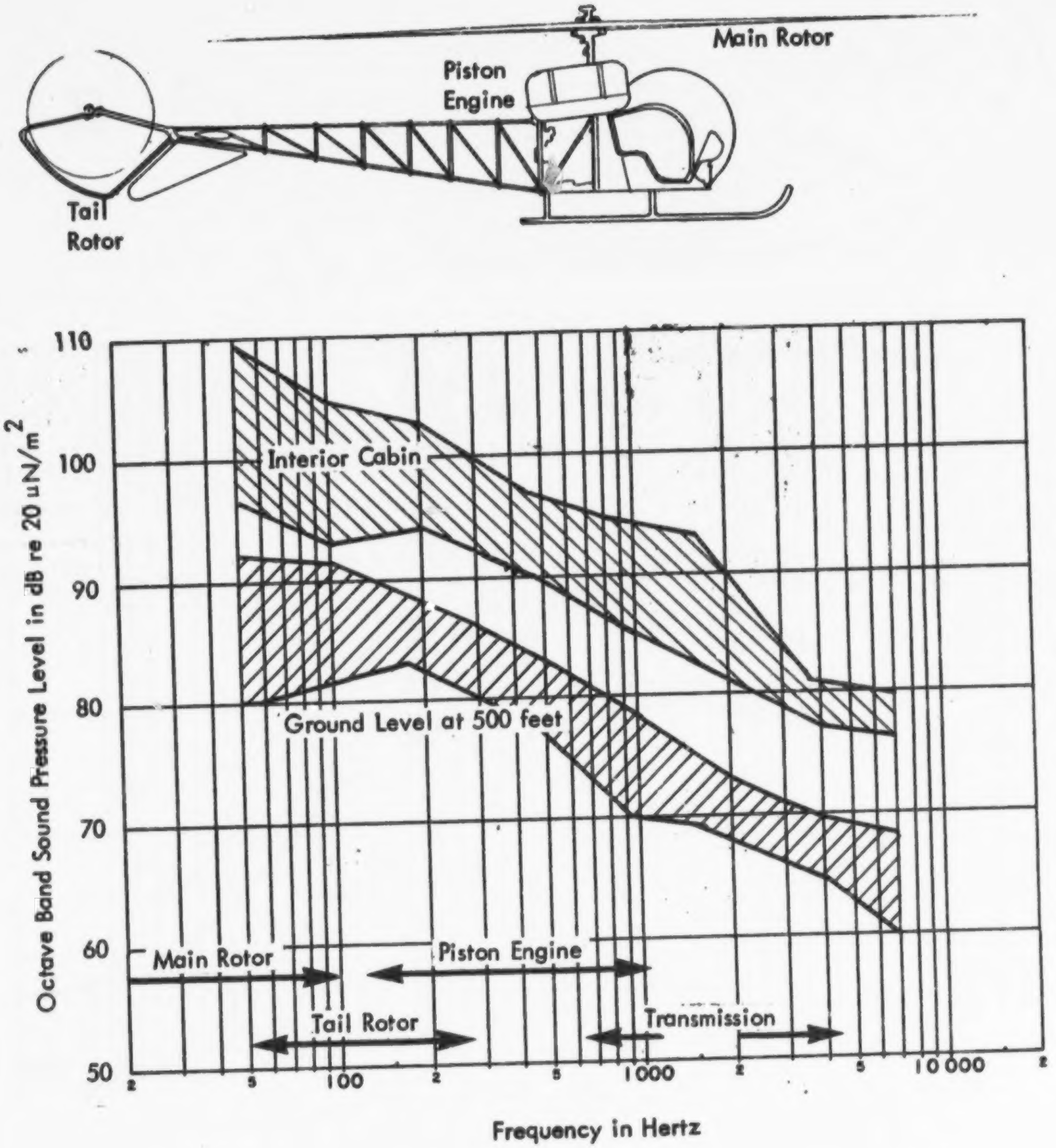


Figure 2.2-3. Typical Noise Spectra of Light Piston-Engined Helicopters

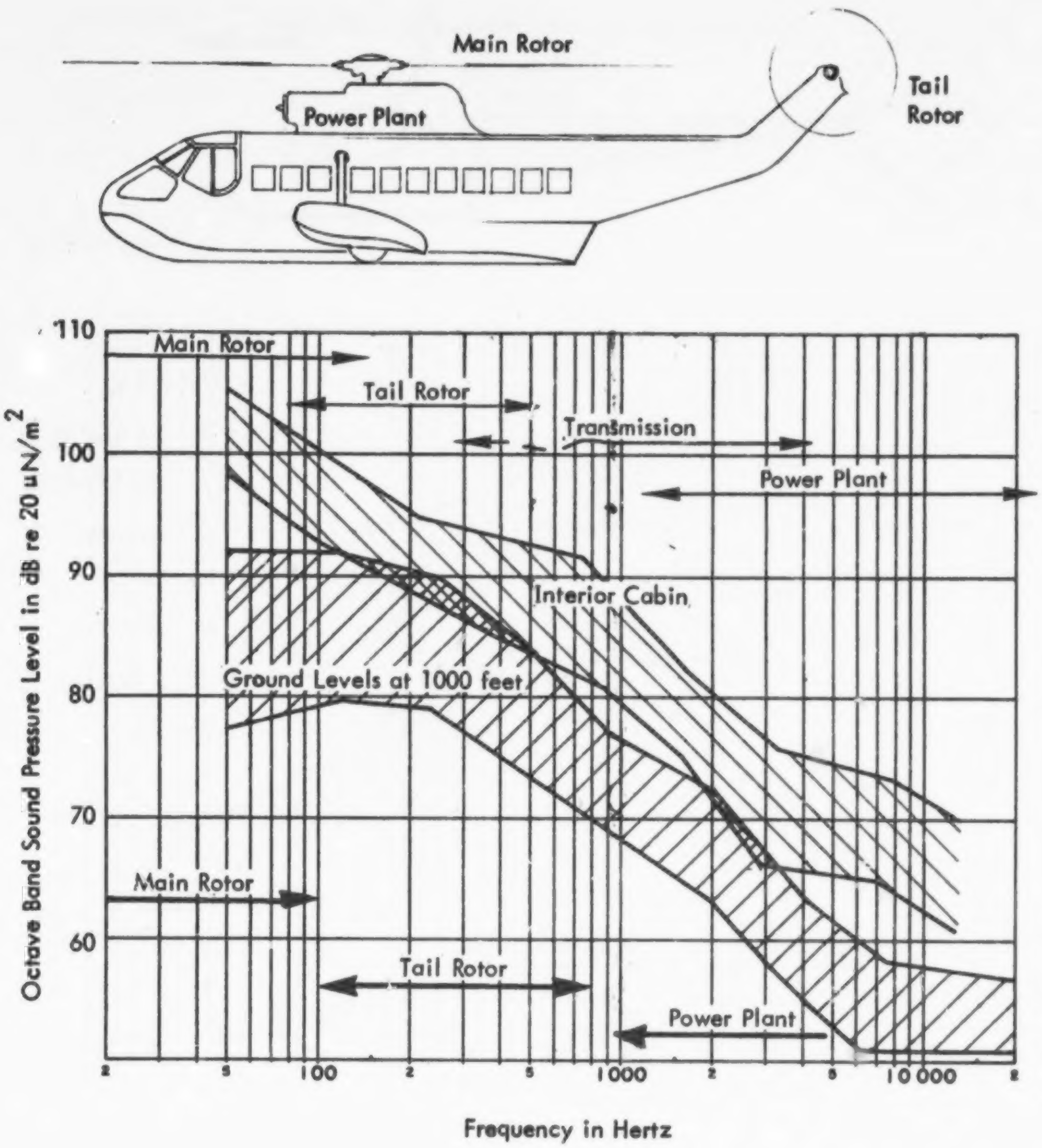


Figure 2.2-4. Typical Noise Spectra of Heavy Helicopters

throbbing or slapping noise of the rotor, analogous to a flashing light compared with a steady one. Most other sources of noise, including propellers, are more analogous to a steady light due to absence of low frequency modulation, and consequently are better assessed by the current scales. Other noise sources on the helicopter, notably the tail (stabilizing) rotor and piston or gas turbine engine, can be particularly annoying in certain conditions. Additional information relating to the noise generating mechanisms of helicopter rotors is presented in Appendix C.

In areas close to the takeoff/landing terminal, prolonged periods of engine-idle operation during the (dis)embarking of passengers are accompanied by the piercing whine of the gas turbine or the equally disturbing bark of a piston engine exhaust. As the tail rotor is usually direct-geared to the powerplant, it is also rotating at a sufficient speed, during these idle operations, to generate an additional noise nuisance. In some cases, the tail rotor and engine noises exceed the main rotor in subjective (nuisance) impact during flyover. This problem is more common on light utility helicopters which have lower main rotor loading and piston engine powerplant, as shown in Figure 2.2-3.

Other subsources, such as the transmission system between engine and rotors, can be distinguished in the passenger cabin and at very close external regions. Their significance is generally low compared to the rotors and powerplant, but in the few cases where they are notably present, the noise is of an annoying nature if prolonged.

STOL Aircraft

Current design concepts of commercial STOL aircraft are based on a projected requirement for operation from 2000-foot length STOL port runways.[1,2] The economic viability of the proposed STOL fleet relies on both its payload capability and its ability to operate from terminals close to the potential customer – the urban community. Each of these requirements has a distinct bearing on the propulsion systems to be incorporated in the fleet aircraft, and on the noise characteristics to be expected and allowed of STOL aircraft. A tentative limit of 95 PNdB (approximately 80 dB(A)) has been proposed by the FAA to be applied at a 500-foot distance from each aircraft.[15] The airframe and propulsion system industries are vigorously pursuing this noise goal. Consequently, the final flight-ware systems may radically differ from the basic breadboard systems now under test and development. Of these systems, those now in development for application to the 40-80 seat category aircraft are:[10-13]

- Compound (single and twin rotor) helicopters, V/STOL
- Quiet-Propeller, STOL
- Tilt-Rotor, V/STOL
- Prop-Fan, STOL
- Lift-Fan, V/STOL
- Jet-Flap, STOL

Full-scale or model acoustic testing of these concepts has indicated that the 95 PNdB limit can be met by the 40-80 seat passenger V/STOL systems.[16] The typical frequency spectra noise characteristics of the propeller, rotor and prop-fan systems are shown in Figure 2.2-5.[10-14] Note that these spectra do not include the engine-noise contribution. The main difference in the spectra are attributable to the rotational speeds (revolutions per second) and number of blades typical of each system. The prop-rotor is a 3-blade low speed system. The propeller is also a 3-blade system, but operates at about three times typical rotor speeds. The ducted prop-fan has about 12 blades operating at speeds slightly higher than the propeller.

Present estimates of the larger (80-150 passenger) STOL system projections indicate that the proposed 95 PNdB limit at 500 feet will not be met by designs based on current technology. The sideline distance corresponding to the 95 PNdB level is projected to be between 3000 and 4000 feet for current designs, and will expectedly converge toward the 500-foot goal as technology is improved.[3]

2.2.3 Environmental Noise Characteristics

The significance of helicopter noise in the community environment is not immediately apparent from the statistics of total number of helicopters in operation. As discussed earlier in the report, the present aircraft noise problem primarily involves

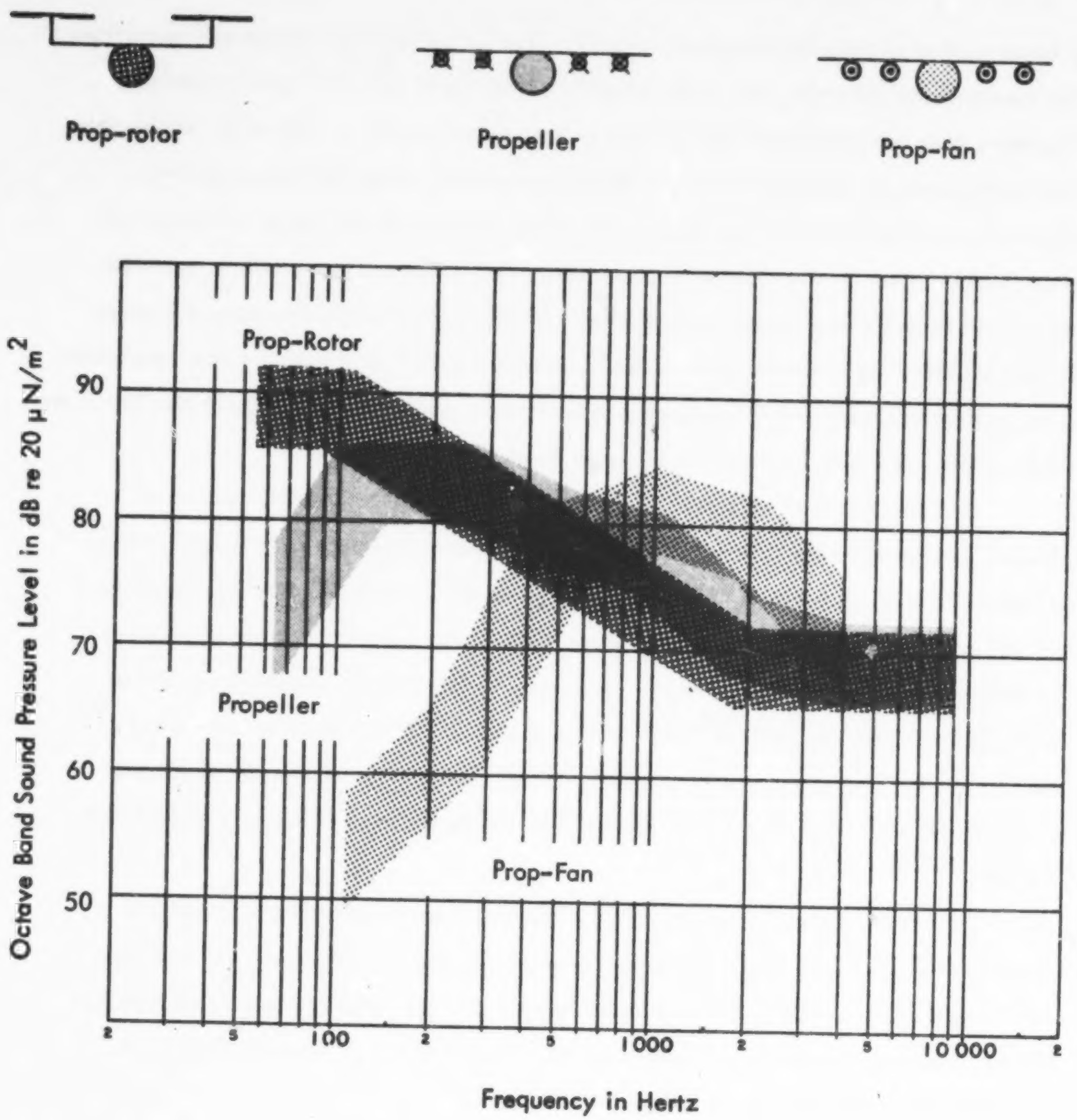


Figure 2.2-5. Typical Frequency Characteristics of Propulsion Systems for 40 to 80 Passenger STOL Aircraft (excluding power plant) at 500 feet

a large number of people living near airports affected by landing and takeoff operations. For conventional aircraft, the cruise condition flight is usually at high altitude and therefore does not contribute much to the ground noise exposure. However, helicopters are most commonly operated at low altitudes due to short stage distances, ground observation requirements of the service, or simply to provide the added attraction of a panoramic view to the intra-city passenger. This extended low altitude operation, most often directly over urban and suburban regions, significantly increases the noise impact potential of the helicopter. The increasing incidence of police patrol operations over populated areas further aggravates this situation due to the prolonged noise intrusion of a hovering or surveying helicopter, operating at low altitude.

Because the helicopter flight route patterns are essentially random at present, it is practically impossible to define their current impact on the environment in terms of exposure duration, land area or population. A sustained public reaction has not materialized, despite the intrusive nature of the sound, probably because of the irregularity of this usage pattern. However, widespread complaints have arisen due to air taxi services in New York, police operations in Los Angeles, and others.[9] This is not surprising since the noise levels at 500 feet from a commercial helicopter are in the 80 - 90 dB(A) range, as are the levels from a police helicopter at 250-foot altitudes.[10-12]

The introduction of the STOL fleet as a convenient commuter mode of transportation will bring many benefits to the urban resident. However, it will also bring a new source of noise into his environment, and the total community acceptance will be dependent on the effectiveness of STOL port planning, aircraft routing, and noise abatement procedures currently being designed.

Figure 2.2-6 shows a comparison of various V/STOL noise levels with those of the community ambient noise levels (L_{90}).[3] A difference of 25 - 30 dB(A) or greater between a single-event intruding noise and the ambient (L_{90}) will annoy many people in the community. If the single event at such a level is repeated sufficiently often, an appropriate community reaction may be anticipated. For example,

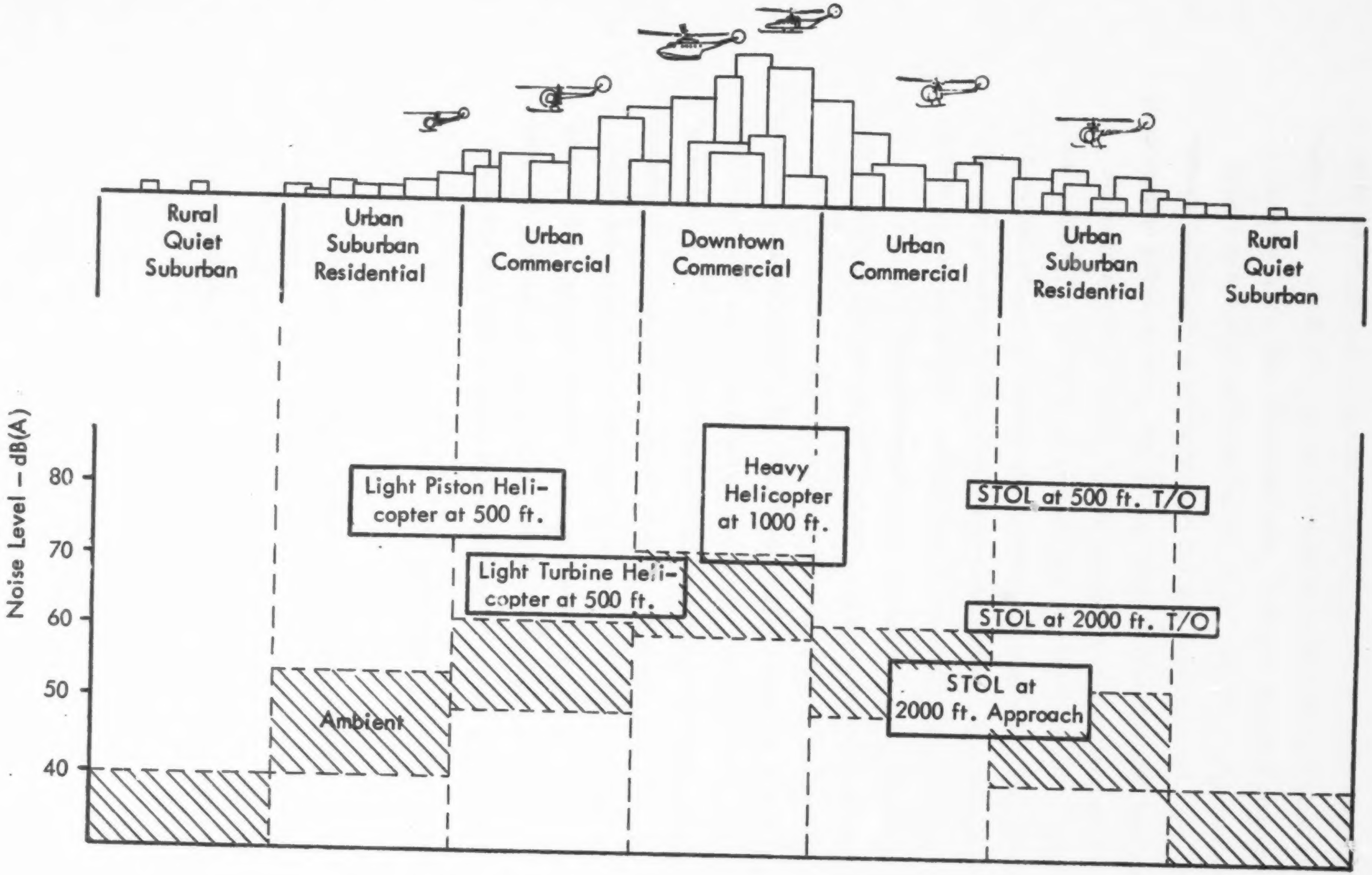


Figure 2.2-6. Comparison of Typical V/STOL Aircraft Noise Levels with Community Ambient Noise Levels (L_{90})

10 overflights per hour during day and evening of a helicopter meeting the 80 dB(A) noise goal would cause a community noise equivalent level of 60 dB(A). No community reaction would be expected in a noisy urban residential community, whereas "widespread complaints" to "threats of legal action" would be expected in a quiet suburban community. To reduce the expected reaction of the quiet suburban community to "no reaction", the minimum altitude over the community should be approximately 4000 feet for this assumed frequency of operation and vehicle noise characteristic.

Figure 2.2-6 also illustrates the problems faced by the city heliport and urban STOL port planner. The desire for central-city operations must be tempered by the constraints imposed by the local outdoor noise levels. Solutions being considered are the use of industrial areas suitable for port locations, and the optimal use of high-rise, non-residential buildings to shield the noise from residential areas.

From the viewpoint of the potential V/STOL passengers, who are predicted to comprise more than half the total revenue passenger complement in 1985[9], the internal noise of rotor and propeller powered vehicles will require significant reduction from their present levels if the service is to be considered attractive. The noise level inside many current helicopters ranges between 90 and 100 dB(A)[10-14], representing a definite risk of hearing damage to the constant traveler, particularly if his exposure exceeds 1/2 hour per day. Also, the occasional passenger may accept poor speech communication during short flights, but the regular-commuter passenger will consider such features a distinct inconvenience. In such cases, it may be expected that manufacturers will attempt to alleviate the problem from a solely commercial standpoint.

2.2.4 Industry Efforts in Noise Reduction

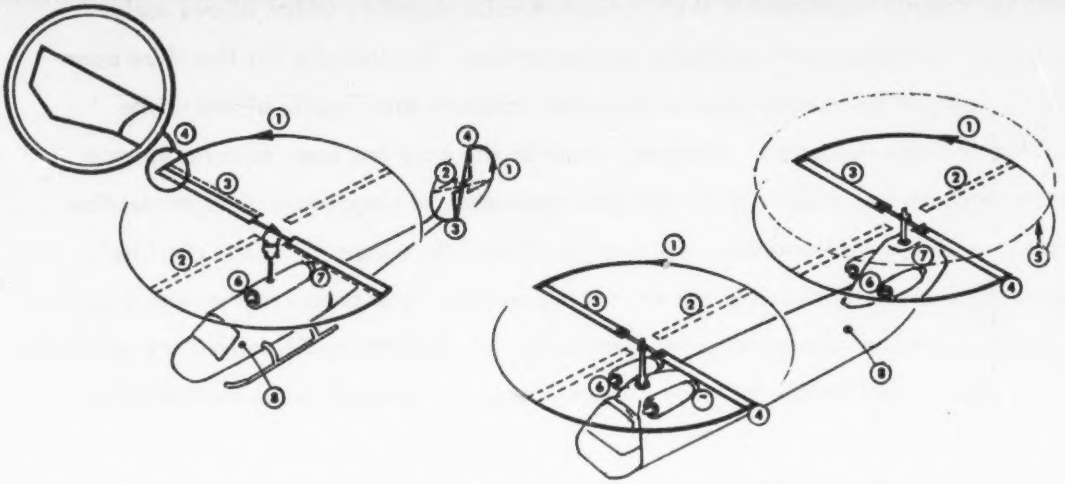
VTOL Aircraft

The helicopter manufacturing industry is primarily engaged in military helicopter requirements, which account for approximately 80 percent of the more than 20 thousand production vehicles produced prior to January 1970.[17] The vulnerability of military helicopters during reconnaisance or evacuative missions has been closely correlated to their excessive noise signature which allows early detection and consequent retaliatory enemy action. The industry has therefore been keenly engaged in research and development programs specifically aimed at the problem of noise reduction. However, much of the work has been directed toward the development of modification concepts applicable to long-established production models or economically viable to production lines. As almost all of the civil helicopter fleet are direct derivations of military models, later production models have benefited from the noise suppression developments. Retrofit modifications are generally not economically feasible for many private operators, although made available by the industry.[18,19]

Another approach taken by the industry toward noise alleviation has been in educating the private operator in particular methods of operation which avoid prolonged community noise exposure and which circumvent the condition of blade-slap noise during descent maneuvers.[19] These and other facets of the industry's awareness of the noise problem relate to past and immediate production helicopter types which will tend to dominate the civil market for the next decade.

The responsibility for developing noise suppression techniques for helicopters has been firmly implanted in the manufacturing industry because of the encompassment of aerodynamic structural design and performance considerations in the acoustic technology matrix. The emphasis of past and current programs has been in the specific area of rotor and propeller noise reduction because of its predominance in the acoustic signature of most V/STOL aircraft, although significant attention has also been given to engine and transmission system quieting. The latter is important when it is realized that almost 50 percent of the light utility helicopters in operation in 1970 were piston-engined and that most of these have unsatisfactory exhaust mufflers as original factory-installed equipment.[18,19]

An illustration of programs related to helicopter design is presented in Figure 2.2-7.[10,13,18,20] Examples of the noise reduction benefits attainable by these approaches are shown in Figures 2.2-8 and 2.2-9, and are indicative of what



① Lower revolutions per second
② More blades
③ Large blade area
④ Modified blade tip shapes
⑤ Reduced blade interaction
⑥ Engine inlet suppression
⑦ Engine exhaust muffling
⑧ Cabin insulation improvements

Figure 2.2-7. Current Design Approaches to Helicopter Noise Reduction

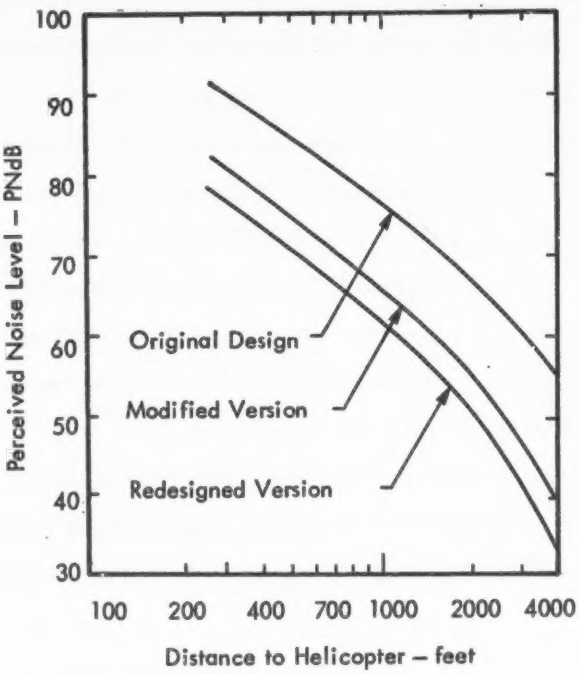
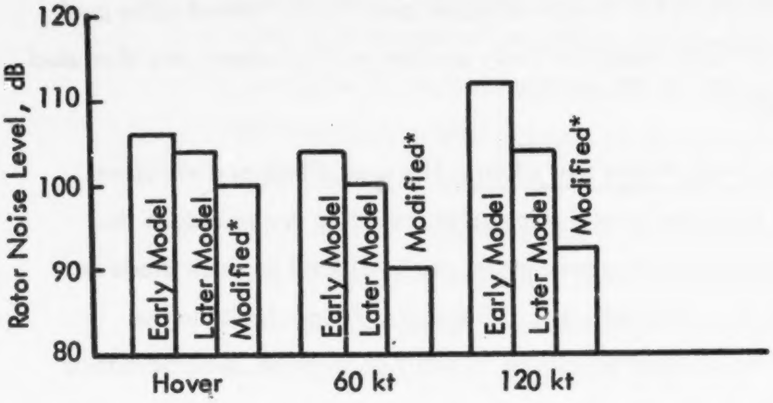


Figure 2.2-8. Effect of Design Changes on a Light Helicopter Noise Signature (Demonstrated)



*Rotor Blade Modifications

Figure 2.2-9. Demonstrated Noise Reduction of a Heavy-Helicopter Twin-Rotor System

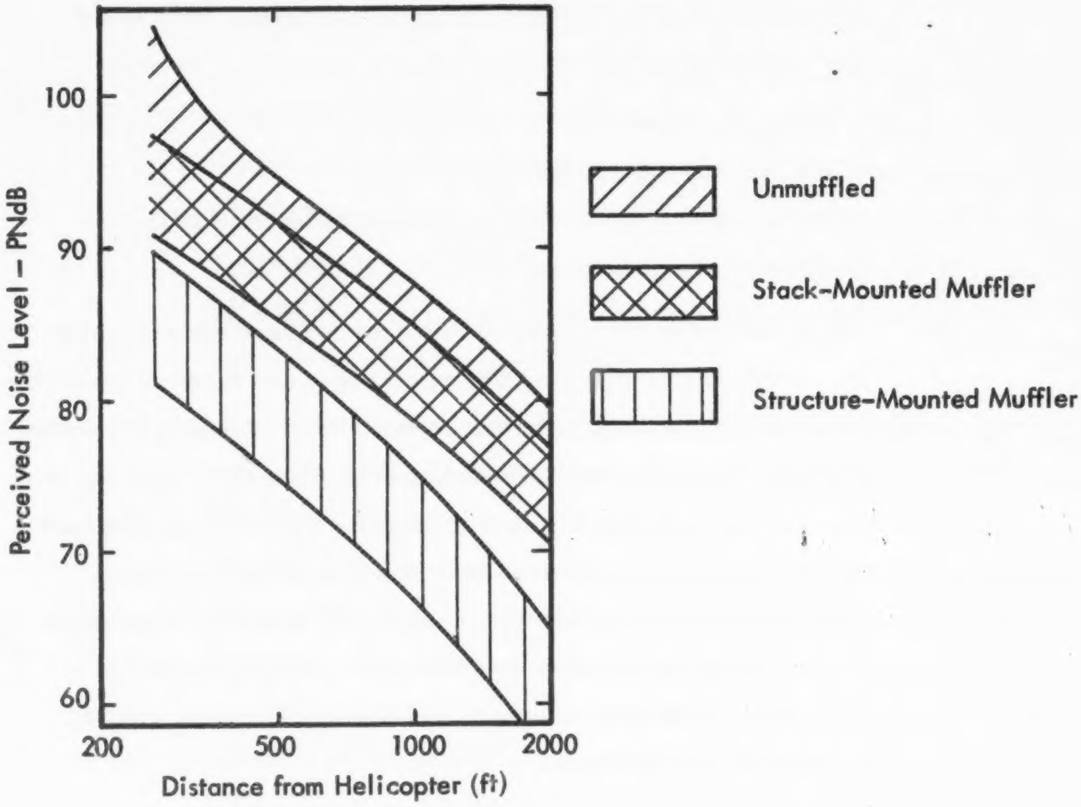


Figure 2.2-10. Exhaust Noise Suppression of Light Piston-Engined Helicopters

can be expected in future helicopter models designed specifically toward noise goal objectives. Major areas of noise reduction study pursued by the industry are discussed in the following paragraphs.[10-13,19]

- Propeller/Rotor Noise Reduction – The most direct and efficient methods of propeller and rotor noise reduction are to reduce the blade tip speed and reduce either the total load on each blade or the load per unit blade area. There are obvious limits to the application of these principles in addition to those of aerodynamic stall (which gives a sudden noise increase) and the weight/performance requirements for economic operation. Thus, most research effort has been aimed at deriving more subtle approaches to design, whereby the above methods can be implemented and improved upon with negligible performance penalty. Some of the more successful of these methods are:

  - Larger blade area
  - Increased number of blades
  - Variable geometry blades (changeable camber in flight)
  - Modified blade tip shapes

  All of these have either resulted from, or have been made practical by, combined efforts in acoustic, aerodynamic and materials research. In particular, the noise reduction potential from increasing the number of blades and blade area has been known for quite some time, but this approach has only recently become practical due to the development of lightweight construction materials and fabrication techniques. Blade tip shape modifications have undergone extensive investigation for both aerodynamic and acoustic benefits, including reduction of blade slap. Helicopter rotor tests indicate that 5 to 8 dB can be achieved by this approach.

- Engine Noise Reduction – At ground-idle and in-flight conditions with noise abatement procedures in operation, the loudest component sound of a V/STOL aircraft may be its engine noise. For piston-powered helicopters, the exhaust noise is extremely noticeable in the signature. Gas turbine engines are distinguishable by high frequency whine of their compressor stages and by their exhaust when the jet is used as a propulsive force. Each of these can be treated by different types of suppression, from the relatively simple piston-engine muffler to the more complex jet-exhaust suppressor. However, all methods cause some degradation of the performance-cost ratio of the vehicle, and consequently the buyer/operator is often reluctant to include them in his optional equipment list. The manufacturer/seller is also reluctant to include them as standard equipment because of the sales competition within the industry and his desire to provide the most economically operable item. Nevertheless, the equipment for noise suppression has been developed, demonstrated, and made available by the industry and other independent companies in the form of retrofit kits composed of factory-installed options. Although much remains to be done to improve the noise and performance influence of suppression devices, an immediate improvement can be obtained if their usage is required.

  The noise reduction currently attainable by available mufflers for helicopter piston-engine exhausts is shown in Figure 2.2-10.[10,19] Stack-mounted units are very lightweight and are designed to fit directly onto the exhaust port of the engine. The acoustic performance of these units ranges from relatively poor to moderate, but they are designed to impose little penalty on operating costs. Structure-mounted types are heavier and more efficient in noise reduction, but are more expensive and in particular have the greatest detrimental effect on operating costs.

Gas turbine (jet) powered helicopters are generally quieter than their piston-engine counterparts, as shown in Figure 2.2-11;[19] however their market popularity is restricted by a requirement for specialized fuel. Again, the main noise problems are associated with their terminal operation rather than their cruise mode. In this case, both the inlet and exhaust require noise suppression treatment, and absorptive vanes or lining installed within the appropriate ducting has been demonstrated to provide a total reduction of up to 10 dB with a resultant power loss of about 1 to 2 percent.

The past 5 years have seen a most significant advancement in V/STOL noise control. Methods of noise suppression have been developed which can, if applied to new production models and the noisier of the older types, allow the full development of the V/STOL as a community service item. Until recently, little attention has been given to the design of the actual landing site to alleviate the noise radiated to nearby residential areas. In fact, the tendency of some operators is to deliberately aim for line-of-sight pads in order to advertise their service. This practice is highly undesirable from a noise nuisance viewpoint. Recommended practices, or even mandatory regulations, should be developed for city heliport design and construction.

In summary, the industry is acutely aware of the noise problem and its relationship to the development of an expanding market for their products. It has been involved in considerable research and development study (at both Federal and industry expense) to find practical methods of reducing the noise levels of current and future production line models. The present situation is that these efforts have been significantly successful, but only in terms of present helicopter usage patterns. The expected increase in intra-city transport and law-enforcement usage will change this pattern over the next decade. This change must be accompanied by further noise reduction built into the helicopter and by more detailed study of urban helicopter

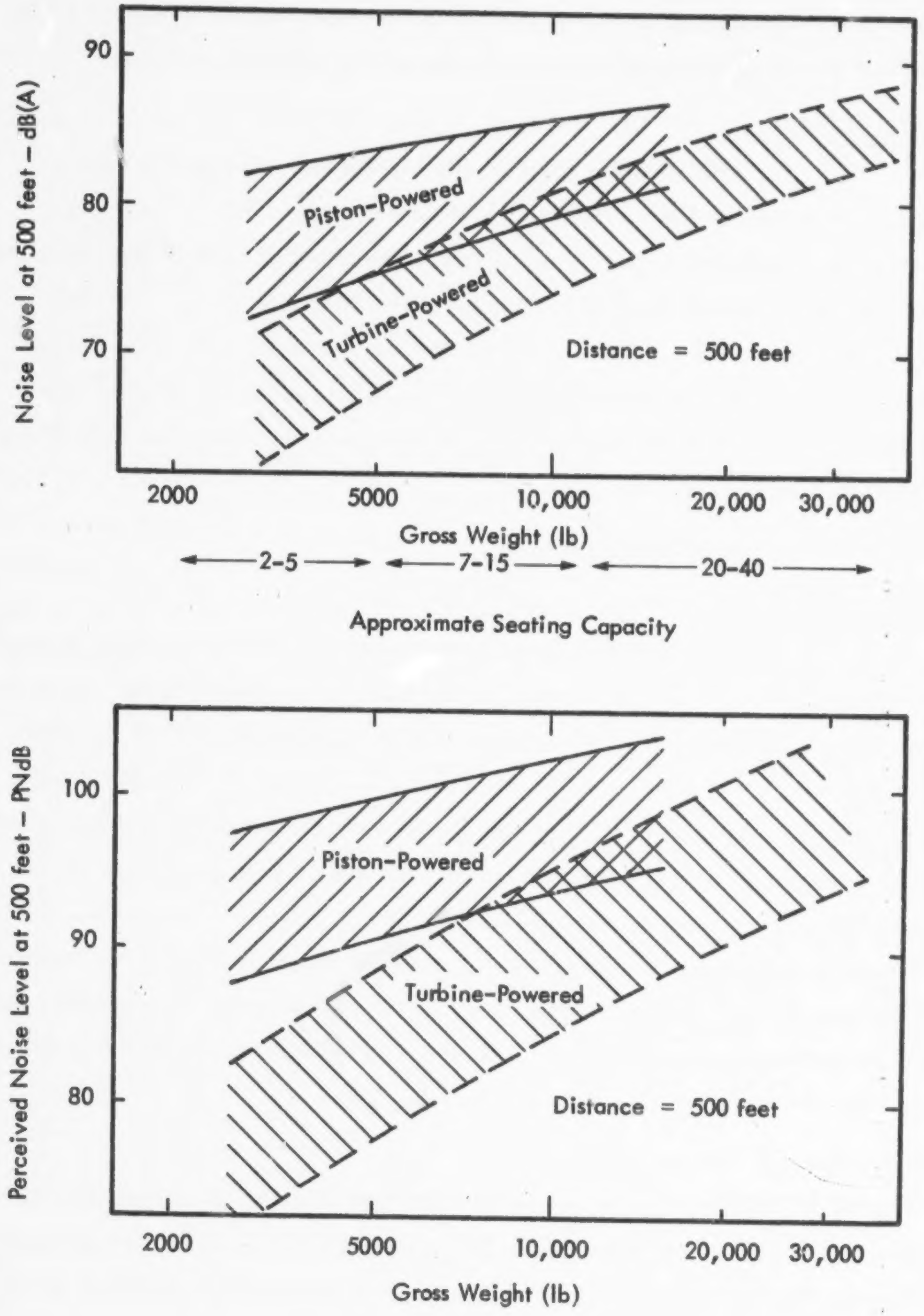


Figure 2.2-11. Trend of Helicopter Noise Levels with Gross Weight and Seating Capacity

structures, location and operating procedures, to ensure that the helicopter fleet will not impose an unacceptable noise burden on the community it serves.

STOL Aircraft

The STOL industry has a tentatively-defined noise goal to meet to ensure its command of the commercial aviation market by 1985.[15] This goal is being approached by intensive research and development of suitable propulsion and lift concepts, some of which have been described in Section 2.2.2. The main difference between the VTOL and STOL industries is that the latter must include noise as a major parameter in their conceptual design studies, whereas the predominant objective of the VTOL (helicopter) industry is to reduce the noise of their established design models.

2.2.5 Noise Reduction Potential

VTOL Aircraft

The most immediate problem for the VTOL industry is to further develop its noise suppression technology to make it economically acceptable to the commercial and private operator. With the increasing usage of helicopters within the urban service system, it can be expected that community reaction to the noise intrusion will also increase and force legislation of operational characteristics to be developed and imposed. It has been demonstrated that significant noise suppression can be installed on current design concepts and therefore it is practical to consider that the helicopter can become compatible with community usage. However, the result can only be achieved by incorporating noise reduction methodology into vehicles produced for the urban-user market as a standard procedure. The potential for future helicopter (VTOL) noise reduction is summarized in Table 2.2-1.

STOL Aircraft

The long term future of the interurban STOL aviation economy depends on the development of the larger (80 to 150 passenger) STOL bus. Current projections indicate that with present technology the 95 PNdB goal will not be met at the 500 foot

Table 2.2-1

Estimated Noise Reduction Potential for Helicopters

Time Period	Noise Reduction, dB[1]		
	Heavy Transport Helicopters	Light and Medium Turbine-Powered Helicopters	Light Piston-Powered Helicopters
Short Term Potential Utilizing Available Production Methods	0	5	10
Long Term Potential Utilizing Current Industry Trends	10	15	10
Long Term Potential Utilizing Demonstrated or Advanced Technology	10	17	20

(1)Noise reduction relative to typical current noise levels in dB(A) at 1000 feet.

distance.[3] This would mean that a large section of residential area around STOL ports would be subjected to unsatisfactory noise intrusion levels. Further, many quiet suburban communities under the STOL flight path would be exposed to excessive noise unless the aircraft cruise altitude were increased enough to achieve compatible ground noise levels. The economic tradeoffs between source noise reduction and higher than optimum airspace altitudes must receive careful study.

2.3 General Aviation Aircraft

2.3.1 Introduction

The term "general aviation" refers to all civilian aviation activity other than that of the commercial air carriers. Within this broad definition, general aviation includes a wide variety of aircraft uses. The following use categories may be considered:[1, 2]

- Business Aviation – This is the largest single category of general aviation in terms of total aircraft hours flown. It includes all aircraft used by corporations and individuals for business transportation. About one-third of the total hours flown by general aviation aircraft fall into this category and these hours are flown by about one-fourth of the registered general aviation aircraft.
- Personal Flying – This covers over half of general aviation aircraft registered in the United States. This category is generally made up of smaller and less expensive aircraft than those in the business aviation group.
- Air Taxi, Charter and Contract Usage – These aircraft are generally considered part of the general aviation fleet. Also included in this category are small charter aircraft contracted with a flight crew.
- Instructional Usage – This category accounts for about one-fourth of the total general aviation aircraft hours flown. However, in numbers of aircraft, instructional aircraft comprise only about 11 percent of the total fleet. Most of these are smaller single-engine types.
- Aerial Application, Industrial and Special Use – This includes aircraft used for agricultural spraying purposes, patrolling, advertising photography, aerial surveying and equipment testing. This category is relatively small both in terms of numbers of aircraft and hours flown.

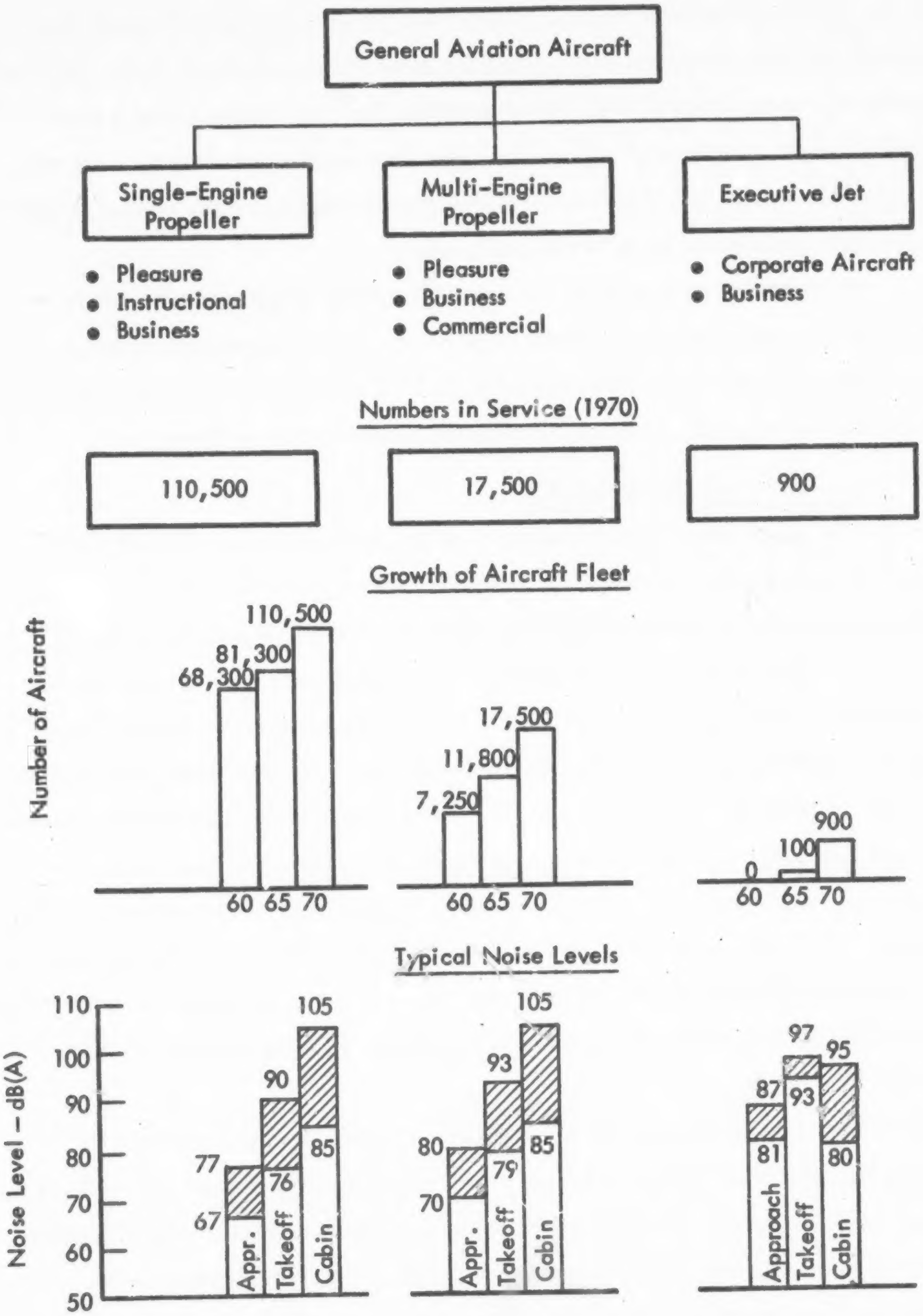
The use of general aviation aircraft has grown in the past 10 years from 12 million flight hours to a total of 25.5 million aircraft hours flown in 1970. Equally significant, the composition of the general aviation fleet has changed from a predominance of small, single-engine propeller types to a much more complex fleet mix. Figure 2.3-1 summarizes this fleet mix and provides information on the number of aircraft operations and typical noise levels produced.

A conservative picture of the economic impact of general aviation is obtained from the fact that manufacturers of airframes, power plants and avionics employ 23 thousand people and had gross sales in 1970 of about $375 million. In addition, $240 million of gasoline was utilized by the general aviation fleet.[3]

2.3.2 Source Noise Characteristics

The noise associated with general aviation propeller aircraft with both piston and turbine engines is produced principally by the propellers. This noise contains a harmonic series of discrete frequency tones, with the dominant fundamental tone typically in the range from 50 to 250 Hz.[4] Depending on the propeller blade shape and the propeller operating environment, the second and third harmonic tones may also have significant levels. Figure 2.3-2 shows typical noise levels and spectra measured during propeller aircraft operations.[4] The broadband and discrete frequency noise above approximately 250 Hz consists of higher propeller noise harmonics, discrete frequency noise from the engine and exhaust, and exhaust broadband noise. The latter noise sources may contribute measurably to the total noise generation by some types of general aviation aircraft, but are generally masked by the propeller noise. Additional information on the noise generation mechanisms of propellers is contained in Appendix C.

The noise characteristics of jet-powered general aviation aircraft, or executive jets, are shown in Figure 2.3-3. Their characteristics are similar to those of commercial jet aircraft. Most business jets are powered by pure turbojet or low bypass ratio turbofan engines; thus, the jet exhaust is the dominant source of noise. Since these engines are much smaller than those used to power commercial jet aircraft,



Approach and Takeoff Levels Measured at 1000 feet

Figure 2.3-1. Characteristics of General Aviation Aircraft

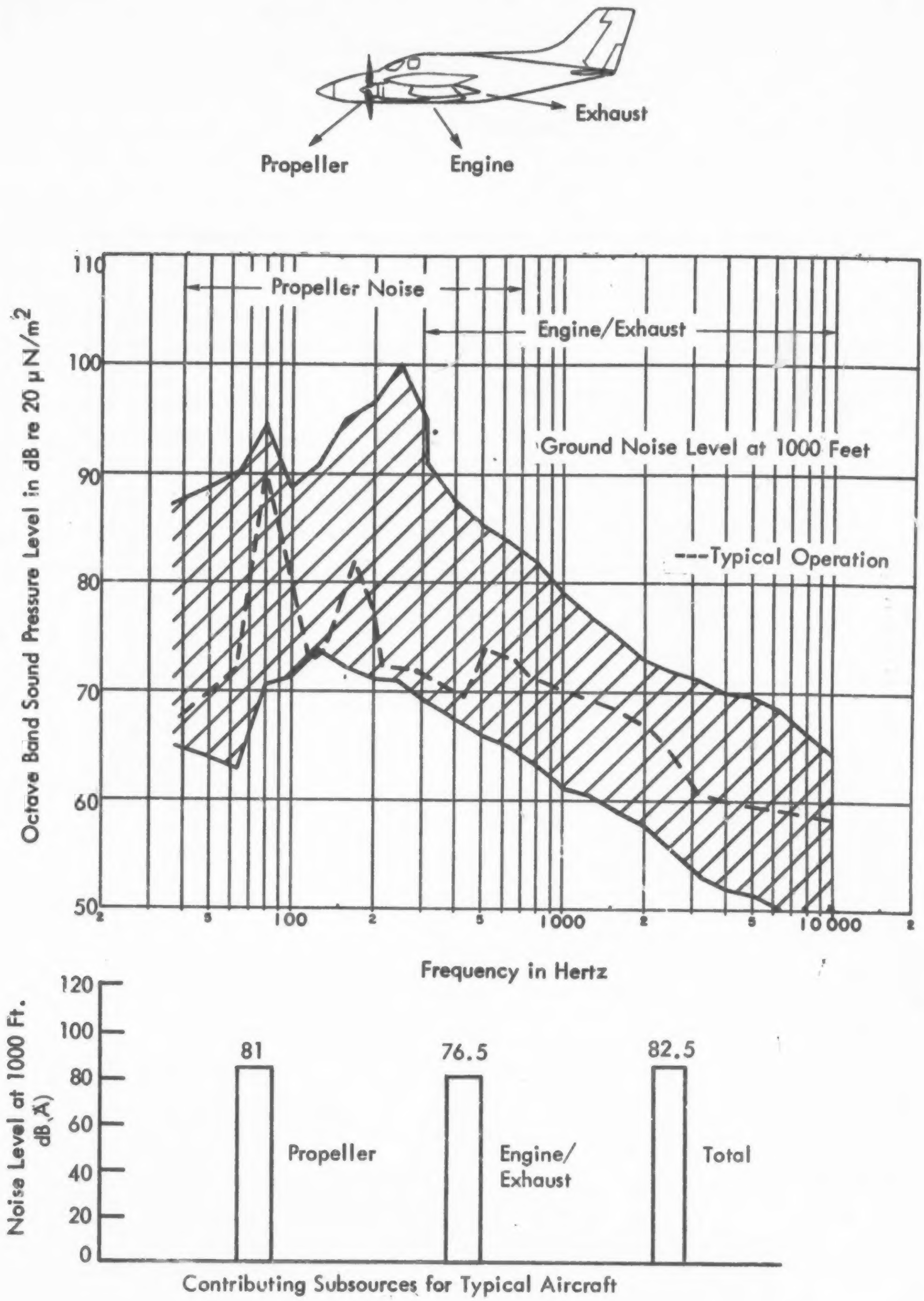


Figure 2.3-2. Noise Levels and Spectra of General Aviation Propeller Aircraft

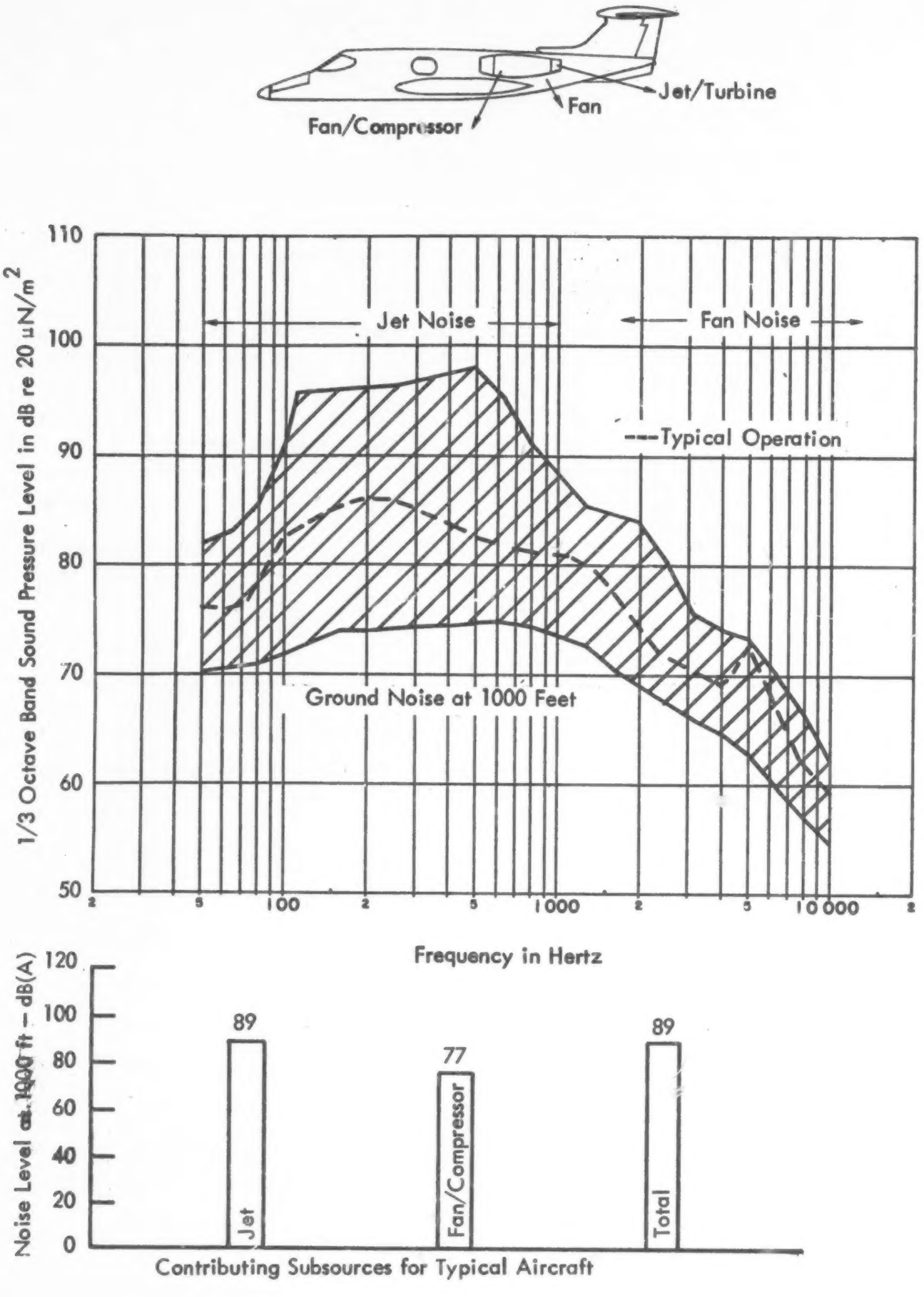


Figure 2.3-3. Noise Levels and Spectra of Executive Jet Aircraft

the characteristic frequencies in the jet noise are higher, and also the noise levels are lower than for the big turbofan engines.

2.3.3 Environmental Noise Characteristics

The operator or passenger in a general aviation aircraft is subjected to noise levels of about 90 dB(A), which is 5 to 15 dB higher than in a commercial jet aircraft. Figure 2.3-4 shows a typical interior cabin noise level for a general aviation propeller aircraft.[5-7] This high noise environment is caused by several factors:

- The engine is mounted close to the cabin, hence the cabin walls are exposed to the highest sound pressures generated by the propeller without any benefit of attenuation from distance. This situation is aggravated in conventional twin-engine aircraft.
- The dominantly low frequency content of the propeller noise makes conventional fuselage noise insulation techniques rather ineffective.
- The small volume within the cabin limits the effect of interior wall sound absorption.

The airport noise impact due to general aviation aircraft noise is quite small when compared to the impact of commercial aircraft operations. Figures 2.3-5 and 2.3-6 show NEF values versus slant range, respectively for takeoff and landing operations, for the average national mix and the number of aircraft that are expected to utilize a typical general aviation airport. The lack of significant impact is evident on noting that the NEF values stay below 30 even at very close ranges and below 20 for relatively short ranges. Consequently, the vast majority of general aviation airports do not have a serious community noise problem.

The low level of impact associated with executive jet aircraft in this example is due to their relatively small number of operations, despite their high noise levels. However, at several general aviation airports that have a significantly higher rate of operation for executive jets than the national average mix, these aircraft tend to dominate the airport noise picture. This effect is illustrated by the additional

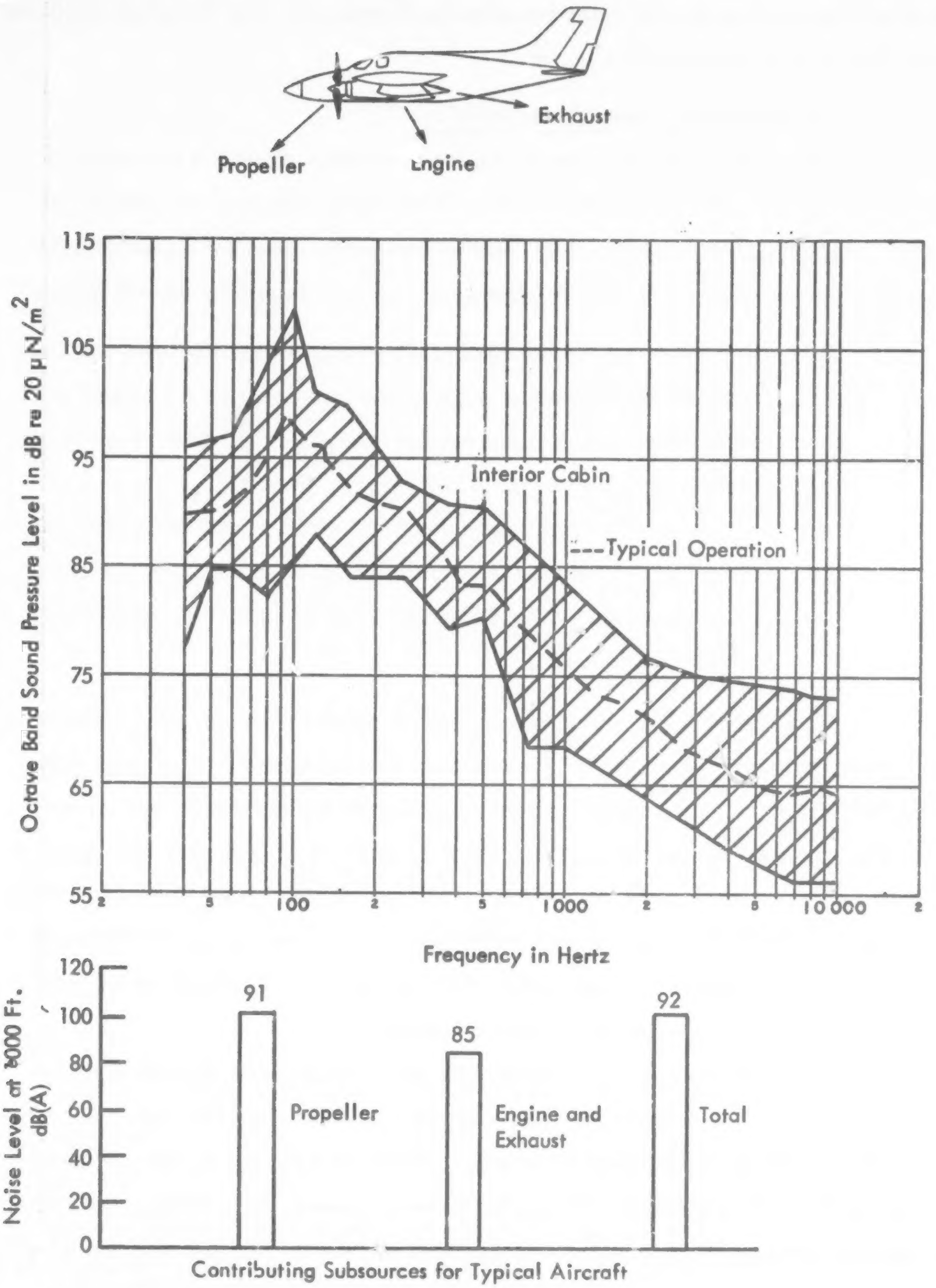


Figure 2.3-4. Interior Cabin Noise Levels and Spectra for General Aviation Propeller Aircraft

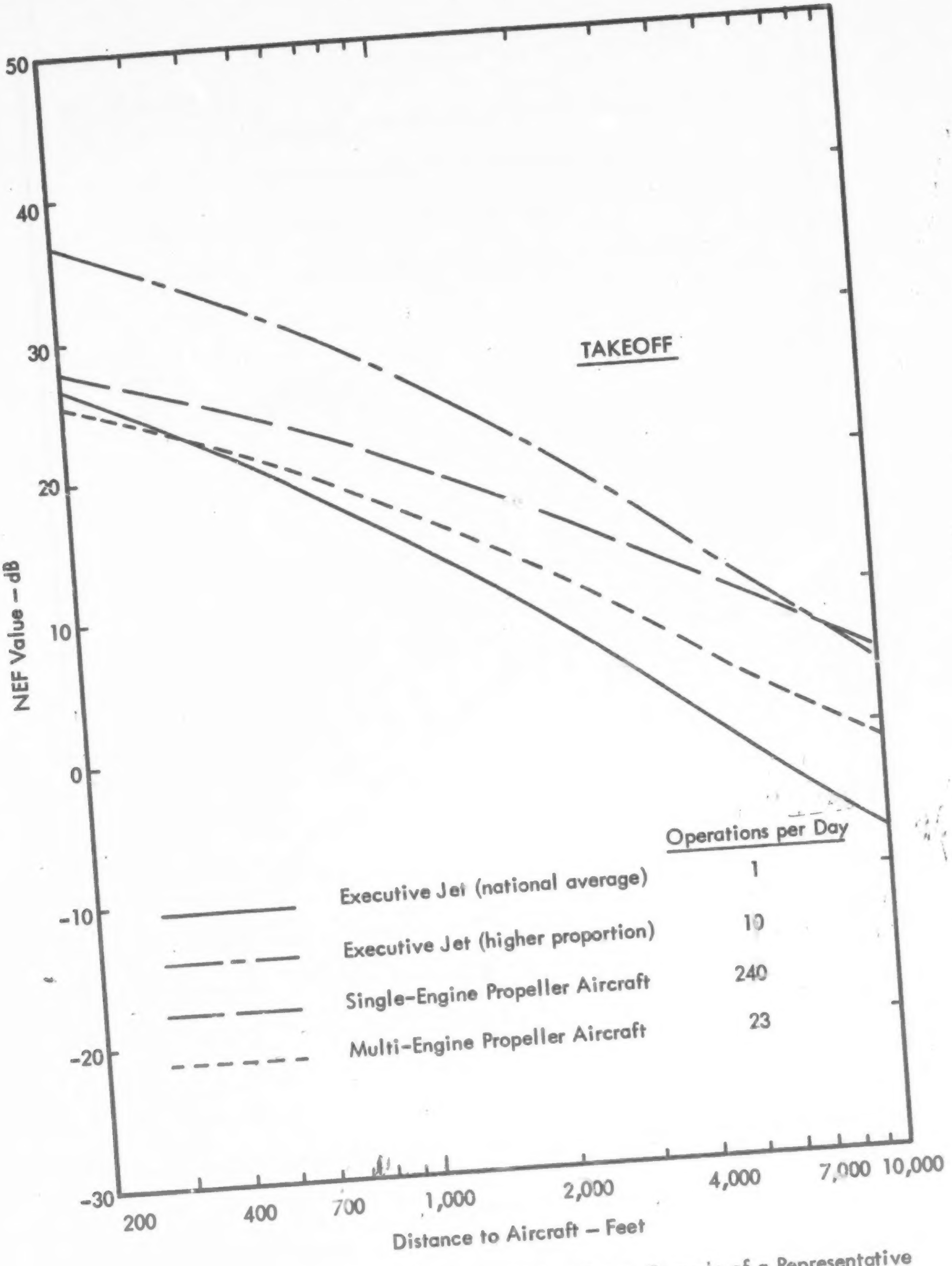


Figure 2.3-5. Noise Exposure Forecast Values for an Example of a Representative General Aviation Airport with Daytime Use Only

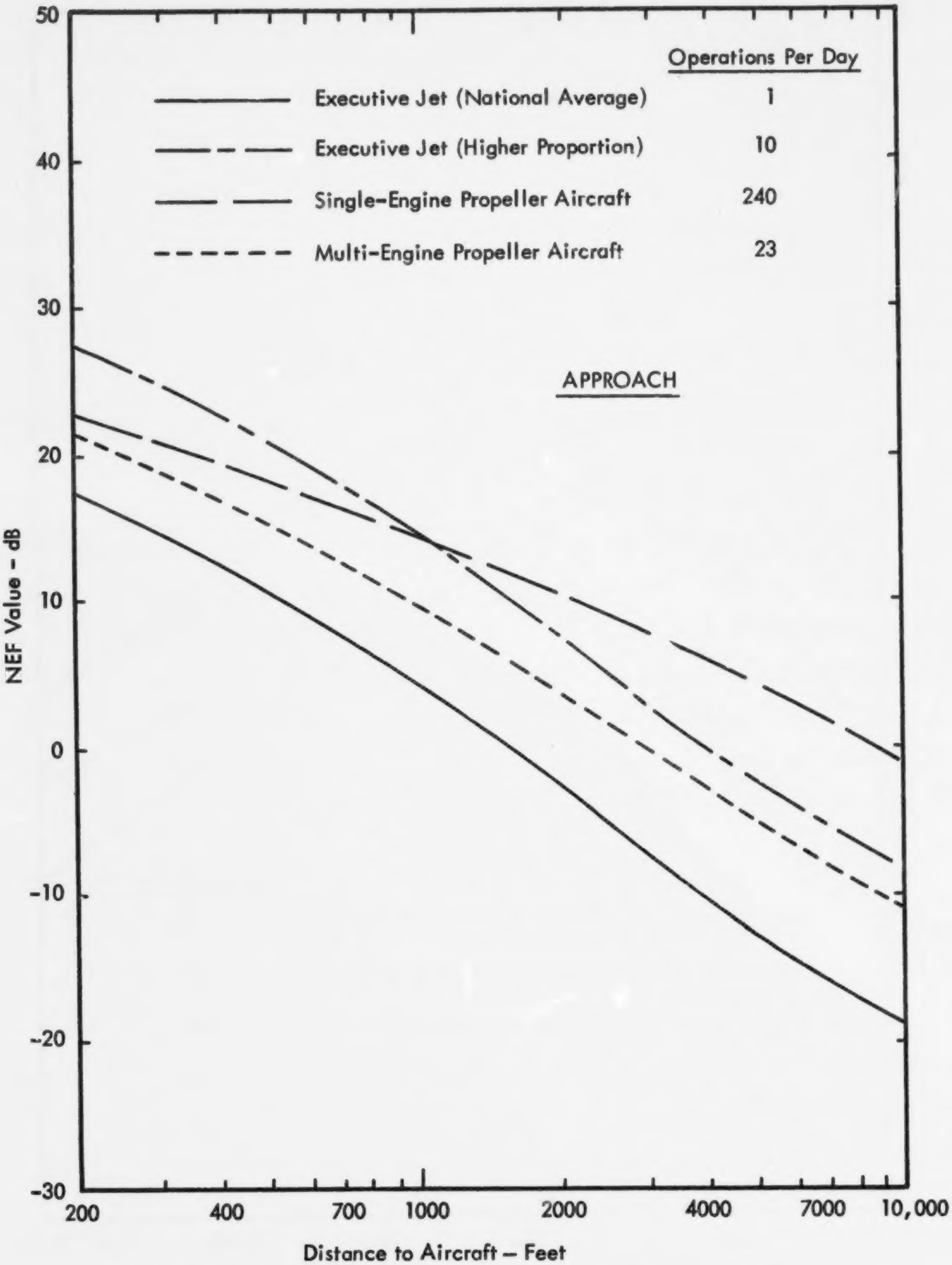


Figure 2.3-6. Noise Exposure Forecast Values for an Example of a Representative General Aviation Airport with Daytime Use Only

business jet curves in Figures 2.3-5 and 2.3-6. In the future, the proportion of executive jets in the general aviation aircraft fleet is expected to increase considerably. Hence, these aircraft may become major noise sources around typical general aviation airports unless their noise levels are reduced.

An additional source of aircraft noise at some general aviation airports consists of the operations of fighter and trainer aircraft of World War II vintage. These airplanes are generally very noisy and tend to create noise problems wherever they are based. The eventual retirement of these aircraft appears to offer the most satisfactory means of alleviating this problem.

2.3.4 Industry Efforts in Noise Reduction

The great majority of all general aviation aircraft are owned by private individuals. More than one-half of these aircraft are used for personal and recreational flying. Therefore, the general aviation aircraft industry deals predominantly with a consumer market similar to that for automobiles or motorcycles. Competitive conformance requires maximum capacity and performance within the particular price class, coupled with economy of operation. The exploitation of technologies such as noise reduction that bear only indirectly on product desirability are consequently relegated to secondary levels of importance. Thus, the consideration of noise in general aviation aircraft is geared to competitive objectives within the industry, rather than to any desired standards.

The industry noise objectives have been aimed at quieting the aircraft interior in order to provide more comfort to the operator or passenger. The approach has been rather cautious and straightforward. Existing quiet engine and quiet propeller technology have been utilized within the constraints of performance, but the main efforts have been directed at cabin noise insulation. Again, the progress has not been spectacular due to the weight penalties associated with noise-insulating materials and the governing performance constraints.

General aviation aircraft are not at the present time a major source of noise pollution. At the hub airports, at which approximately one-half of the aircraft operate, their noise characteristics are masked by the much noisier commercial aircraft. The remainder of the aircraft are distributed over more than 11 thousand airports within the United States.[2] With some exceptions, the noise levels at the general aviation airports have not reached a magnitude at which the environment is severely affected. Thus, the general aviation industry has not, until very recently, considered aircraft noise in terms of the non-participant environment.

The general aviation fleet has grown rapidly during the last 15 years and will continue to grow an an accelerated rate until at least 1985. As is indicated in Figure 2.3-7, what is more important than the total growth in the fleet from noise considerations is the growing number of multi-engine piston, turboprop and turbojet aircraft in the projected fleet.[8] Hence, the typical general aviation aircraft will become noisier. This factor, in addition to the increase in the number of aircraft operations, will lead to an increasing noise pollution potential.

Noise Reduction Programs

As discussed above, the main effort in noise reduction by the general aviation industry has been directed toward lowering the interior cabin noise levels. This objective has been achieved by combining reduced noise generation at the source and improved transmission loss through the cabin walls. Propeller and engine noise reduction have not been actively pursued. However, as discussed in the V/STOL Section, the propeller and engine manufacturers have been engaged in the development of quiet concepts for military and V/STOL commercial applications, and some of the results have fed back to the general aviation industry. As an example, current aircraft models generally have three-bladed propellers rather than the old two-bladed propellers, with a resulting noise reduction of 3 to 5 dB.[9] This result has been made possible through materials technology development by the propeller manufacturers whereby the new propellers weigh less than the older types, despite the increased number of blades.

Reduction of the interior noise levels by means of cabin wall insulation has been the subject of more active participation by the industry. The typical interior

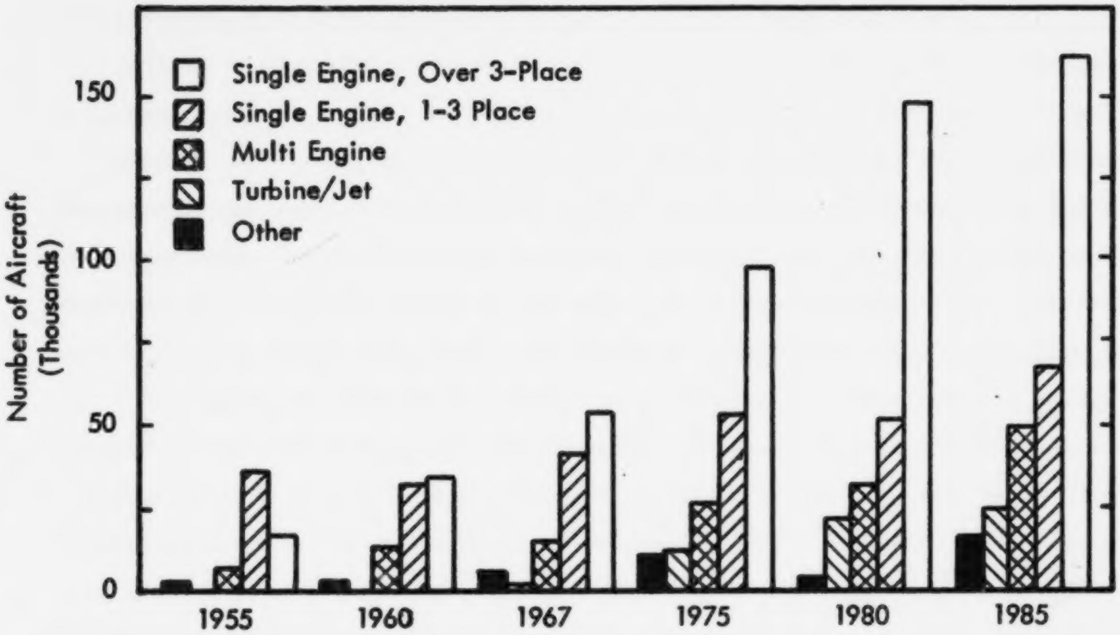


Figure 2.3-7. Number of General Aviation Aircraft with Projections for 1975, 1980 and 1985

noise levels of general aviation aircraft lie in the range of 90 to 105 dB(A).[5-7] Some of the new models on the market have corresponding noise levels down to 85 dB(A),[9] a reduction of 5 to 20 dB of which 5 to 12 dB is due to improved cabin wall insulation.

The executive jet aircraft are typically much noisier than propeller-driven airplanes, but they constitute such a small percentage of the total general aviation fleet that their noise impact has generally been kept within bounds except at some airports which have a much higher than average proportion of jet operations. However, with the projected future growth in the number of executive jets, they may be expected to cause noise problems at an increasing number of airports unless their noise levels are reduced. The jet engines in use by the executive jet aircraft fleet have been developed for military purposes, or as smaller versions of early jet engines for the commercial fleet. Hence, they tend to be objectionably noisy. Only very recently has the general aviation industry actively sought more advanced and quieter jet engines for the business jets. An example of the noise reduction achieved by substituting an advanced technology engine (AiResearch TFE-731 turbofan) for an older type jet engine is presented in Figure 2.3-8.[10] This change will reduce the noise level generated by the Lear Jet at the FAA certification position on takeoff from 96 EPNdB to less than 86 EPNdB. Another example is provided by the Cessna Citation business jet, powered by Pratt & Whitney JT15D turbofan engines. FAA certification figures for this aircraft show noise levels of 76 EPNdB on takeoff and 88 EPNdB on approach at the FAR-36 measurement positions.[11] These figures lie 17 and 14 EPNdB respectively, below the noise levels stipulated by FAR-36. An equivalent noise reduction throughout the business jet fleet would strongly reduce the potential noise impact of these aircraft.

With respect to the suppression of the sources of noise in general aviation aircraft, the industry will, at least in the near future, continue to rely on the powerplant and propeller manufacturers for further developments. These programs are discussed elsewhere in this report; propellers and the associated powerplants are evaluated in the V/STOL Section, and the jet engine programs are discussed under Commercial Aircraft.

The general aviation industry's plans for further reduction in the interior noise levels are formulated in terms of what the expected achievements are, rather than as desirable objectives. Disregarding any possible significant reduction in the powerplant noise levels, an interior noise level of 75 dB(A) is considered possible within the next 10 years.[9] This will be achieved by means of improved cabin wall lining materials and a more sophisticated evaluation of the critical noise transmission paths. This level would represent a considerable improvement over the typical noise levels in the current general aviation fleet, as shown in Table 2.3-1.

Table 2.3-1

Interior Noise Level Objectives[9]

	Interior Noise Levels - dB(A)	Year
Typical Older Aircraft in Current Fleet	90 - 105	
Current Production Aircraft	83 - 85	1971
Objective for Future Aircraft Design	75	1981

2.3.5 Noise Reduction Potential

In order to assess the potential noise reduction in the general aviation fleet, it is appropriate to establish specific noise reduction objectives. Figure 2.3-7 shows that by 1985 there may be 316 thousand general aviation aircraft operating within the United States.[8] However, 58 percent of these are expected to be concentrated within the population hubs, where in many cases their noise characteristics will be masked by commercial aircraft operations. The remainder will be distributed throughout the suburban and rural areas served by approximately 11 thousand general aviation airports. In the low population density rural and outer suburban areas, the

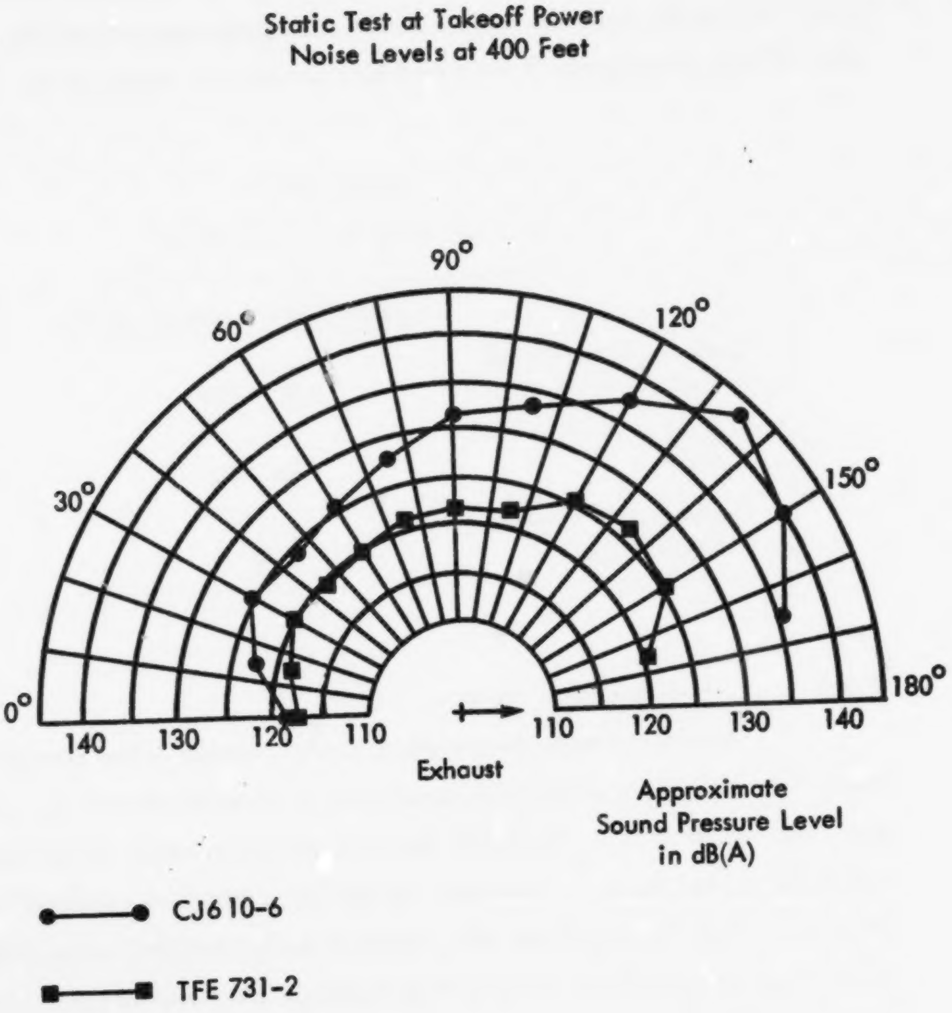


Figure 2.3-8. Comparison of Noise Levels at Various Angles from Engine at Approximately 3000 lbs Thrust

general aviation airports are generally located sufficiently far away from population centers that no significant noise impact is expected, even with the noise levels generated by the current type aircraft. The potential noise problem is thus predominantly associated with the growth of aircraft operations at major suburban general aviation airports. Assuming a normal suburban residential area, median daytime outdoor noise level (L_{50}) of 49 dB(A) and a typical minimum slant range of 500 feet, a single event maximum noise level of 74 to 79 dB(A) may generally be considered acceptable. Figure 2.3-9 compares this range of levels, extrapolated to 1000 feet distance, with the noise levels generated by a variety of current general aviation propeller aircraft.[4] Some light, single-engine airplanes fall within the desired range, but generally a suppression of 5 to 15 dB will be required to meet the suggested criterion. For the business jet aircraft, a suppression of at least 15 dB will be required over that achieved with the current state-of-the-art, as demonstrated by the Lear Jet with advanced technology turbofan engines (discussed in Section 2.3.4).

In order to establish whether these noise reduction objectives are realistic, propeller aircraft will first be considered. As discussed in the V/STOL Section, a reduction in engine/exhaust noise of 13 dB is achievable with current technology. Similarly, a realistic objective for propeller noise reduction is approximately 10 dB over the next 5 years. Extrapolating these values to the 1980's, it appears that a maximum noise level objective of 68 to 73 dB(A) at 1000 feet for general aviation propeller aircraft is achievable.

For business jet aircraft, the potential quiet airplane is evaluated by consideration of the expected possible noise reduction in commercial jet aircraft. Extrapolation of the potential noise levels of the commercial quiet jet engine to the size and thrust required for the business jet aircraft powerplant yields a level of approximately 75 dB(A) at 1000 feet during takeoff operations, which is within 2 dB of the desired result.

It must be emphasized that these noise reduction values refer to new aircraft only. The future potential noise reductions are summarized in Table 2.3-2.

Table 2.3-2

Potential General Aviation Aircraft Noise Reduction

	Noise Reduction in dB	Future Noise Levels at 1000 Feet dB(A)
Propeller Aircraft	5 - 15	68 - 73
Executive Jet Aircraft		
Near Term	13	85
Long Term	23	75

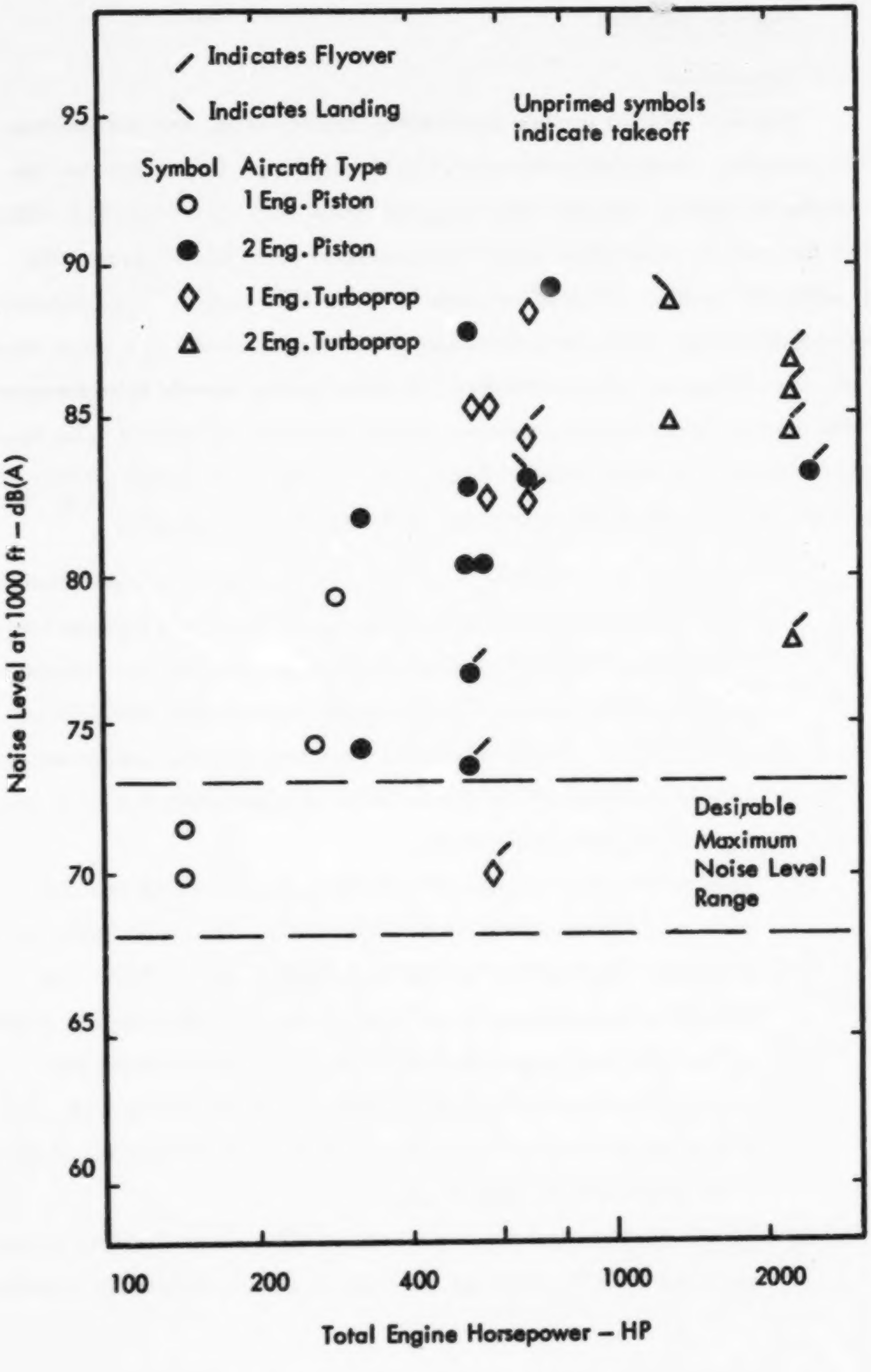


Figure 2.3-9. Noise Levels Generated by General Aviation Aircraft

2.4 Highway Vehicles

2.4.1 Introduction

Highway vehicles include automobiles, trucks, buses, and maintenance and utility vehicles. Motorcycles are treated in the section on Recreation Vehicles. Traffic studies of highway vehicle usage in typical urban areas show that about 1600 to 2300 trips are made by automobile drivers and passengers every day for every 1000 people, while 200 to 400 truck trips are made for every 1000 people. Approximately 40 percent to 45 percent of the latter terminate in residential areas. This urban travel represents about 52 percent of the estimated 3 billion highway vehicle miles traveled in 1970. The general characteristics, numbers, growth patterns, and typical noise levels for highway vehicles are summarized in Figure 2.4-1. Significant factors relative to each type of highway vehicle are summarized in the following paragraphs.[1 - 5]

- Automobiles – Automobiles are the primary mode of transportation in the United States and constitute the largest number of highway vehicles. From 1950 to 1970, the number of automobiles in use has increased from 36 million to 87 million; passenger cars traveled 1000 billion miles in 1970. Automobile sales, including vehicles, equipment and service, reached $92 billion in 1970. Approximately 5 million people were employed by this industry.
- Trucks – The total number of trucks in use has increased from 8.2 million in 1950 to almost 19 million in 1970. Total truck miles increased to 206.7 billion in 1969 from 90.5 billion in 1950. The average annual mileage for all trucks is over 11,000 miles. A majority of the total truck operating hours (194 billion) was in population centers, 86 percent of the time in pickup and delivery service, and the remainder in long haul service. Thirty-nine (39) percent of all truck miles were on urban streets.
- Buses – Highway and city buses accounted for about 27 billion passenger miles in 1970. Mileage has been on a slight decline for a number

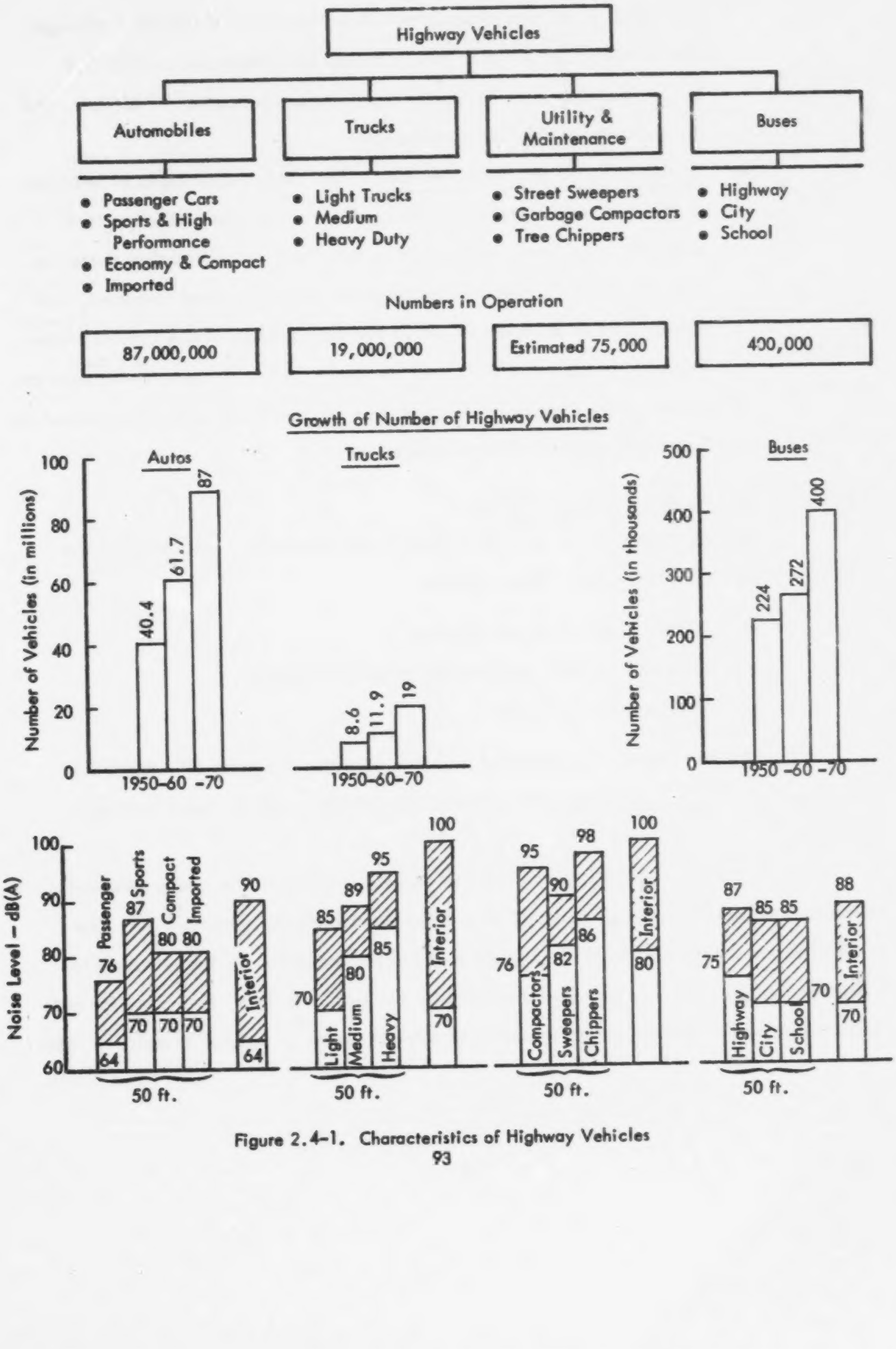


Figure 2.4-1. Characteristics of Highway Vehicles

of years, and bus passengers now constitute 4.2 percent of the commercial total. Around 74 percent of the total of 400 thousand buses are school buses and account for about one-half of the total mileage. The combination of local and intercity bus lines have carried 5.8 billion passengers in 1970, for a passenger revenue of $2 billion, and have employed 150 thousand people.

- Utility and Maintenance Vehicles – The three major types of vehicles in this category selected for study are garbage compactors, street sweepers, and brush and tree chippers. It is estimated that there are approximately 75 thousand garbage compactors, street sweepers, and tree and brush chippers in use in the major cities of the United States. Garbage compactors and street sweepers generally operate 40 hours per week. They usually begin operation by 6:00 a.m. and often extend to Saturdays to meet pickup requirements.

2.4.2 Source Noise Characteristics

The noise levels produced by highway vehicles can be attributed to the following three major noise generating systems:

- rolling stock; tires and gearing
- propulsion system: engine and related accessories
- aerodynamic and body

The noise levels produced by highway vehicles are generally dependent upon vehicle speed, as illustrated for a number of different vehicle types in Figure 2.4-2.[6 - 8]

Figure 2.4-3 illustrates the relative contribution of tire and engine noise to the overall noise levels of automobiles and trucks at highway speeds.[9, 10] The small difference between the 65 mph coast and cruise conditions for the automobile indicates that its noise is generated primarily by the tires. In fact, tire noise for automobiles becomes a significant contribution to overall levels at around 35 mph.[11] The

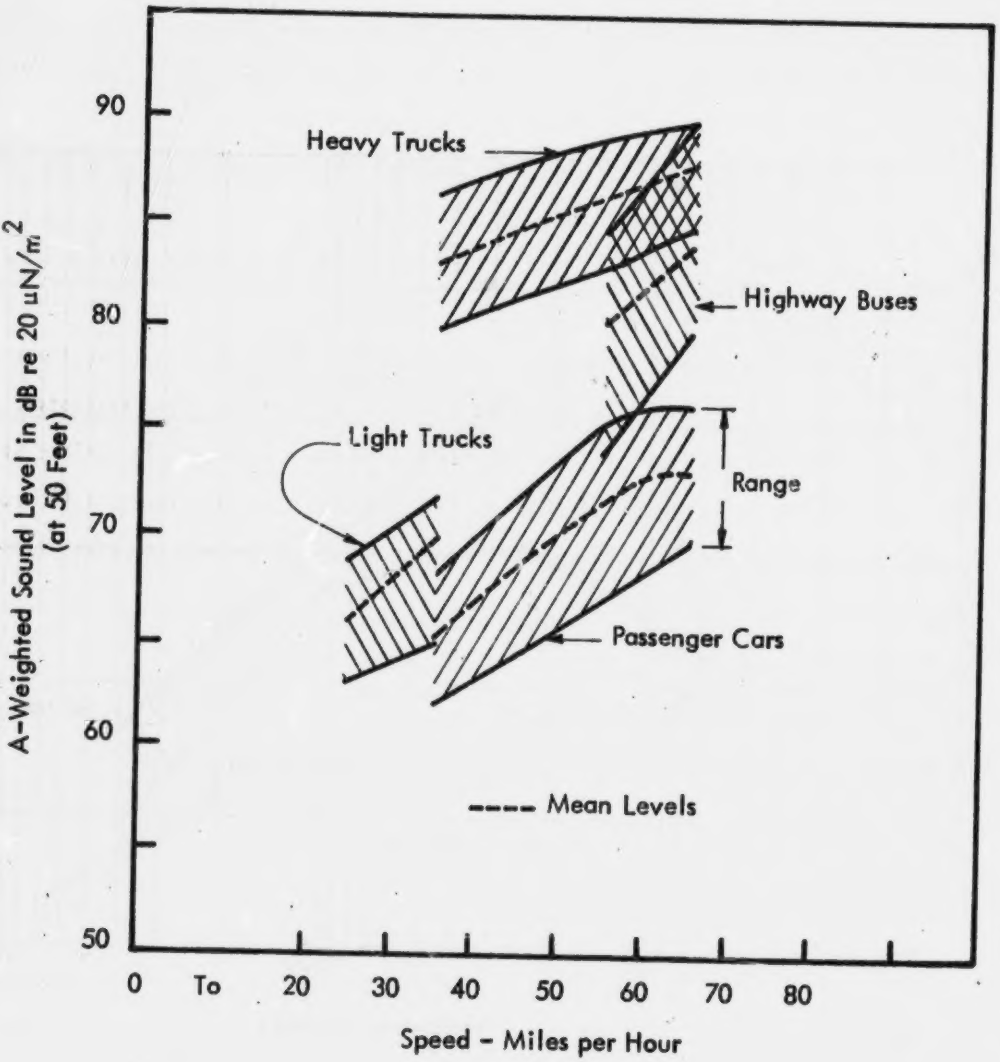


Figure 2.4-2. Single Vehicle Noise Output as a Function of Vehicle Speed

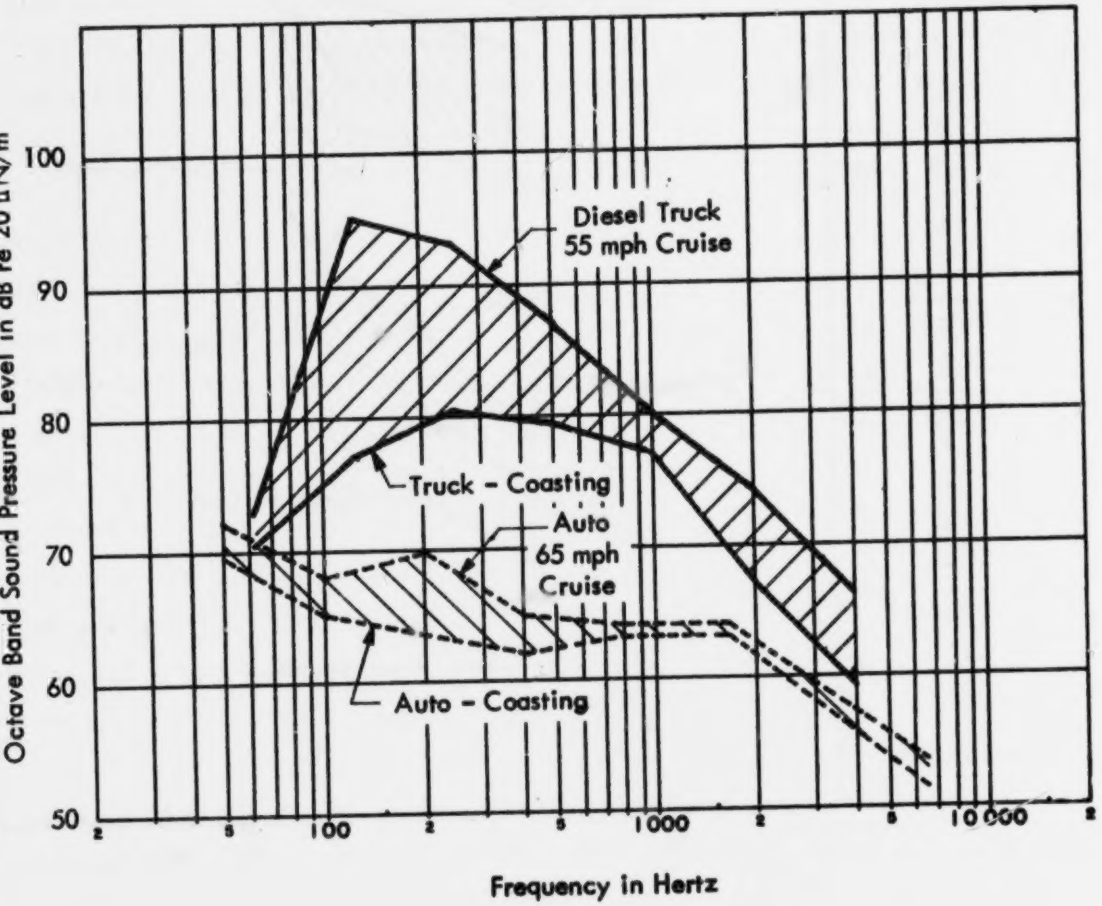


Figure 2.4-3. Diesel Truck and Automobile Noise at Highway Speeds, Cruise and Coasting (at 50 Feet)

tire noise for trucks begins to become important in the high frequency portion of the spectrum at speeds of 45 to 50 mph, although even at 55 mph, engine noise controls the low frequency spectrum.

Tire noise levels vary by 7 to 10 dB, depending upon road surface composition and roughness. Another 5 to 7 dB variation may be expected for truck tires as a function of axle load. In addition, significant variations in noise are found to be a function of tread design and state of wear. At constant speed, these variations may result in a 20 dB range in noise levels.[12 - 14]

Figure 2.4-3 also identifies the segment of the noise spectra contributed by the propulsion system. This contribution is further defined in Figure 2.4-4, which compares the typical noise spectra produced by a heavy diesel truck and by an automobile, both under maximum acceleration at 35 mph.[15] The noise characteristics of propulsion systems may be classified as either acoustic noise radiating directly out of the engine openings, or as noise produced by internal engine processes which then radiate from the engine structure. Figure 2.4-5 illustrates the relative effect of silencing on overall engine-generated noise attributable to these two classifications.[16] The unsilenced exhaust noise is seen to overshadow the total of the other noises by 10 to 15 dB in each octave over the entire audible range. With the exhaust silenced, induction noise is observed to prevail at frequencies below 1000 Hz, whereas noises radiated from the engine structure control the spectrum above 1000 Hz.

The third principal source of noise in highway vehicles includes aerodynamic turbulence and body rattles. It is generally felt that streamlined designs do much to reduce the noise contributions of automobiles and buses at highway speeds; however, application of aerodynamic styling to trucks is not considered practical due to servicing requirements.[17] Body rattles generally reflect the care and maintenance the vehicle has received. These are mainly an annoying factor at low speeds in residential areas and can be controlled only by routine servicing of the vehicle and careful loading of the truck and cargo space.

The following paragraphs provide a discussion of the characteristics of the noise generated in trucks, automobiles, buses and maintenance vehicles. An analysis

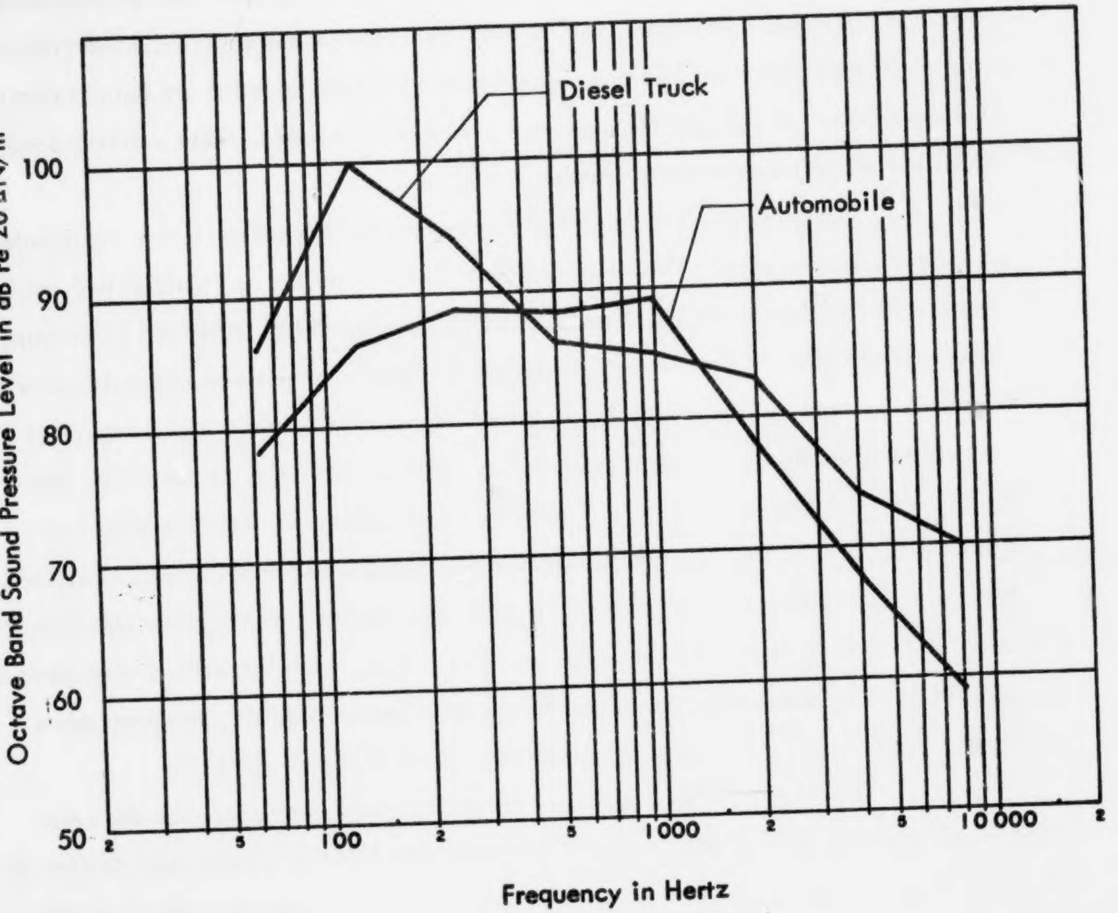


Figure 2.4-4. Typical Octave Band Spectra for Diesel Truck and Automobile (Full Throttle Acceleration at 35 mph at 50 Feet)

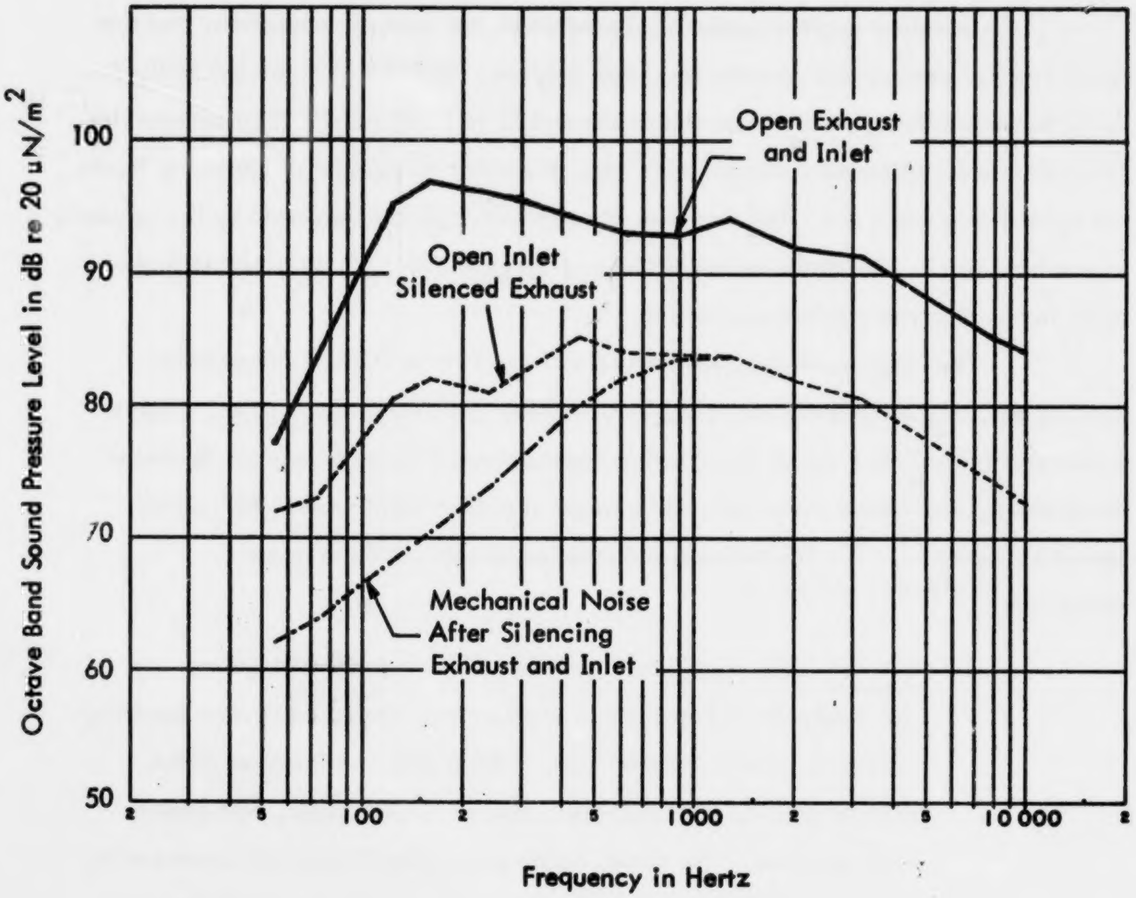


Figure 2.4-5. Octave Band Spectra of Diesel Engine Inlet and Exhaust Noise Illustrating the Effects of Silencing for the Exhaust and the Intake

of the major noise sources for trucks will be provided first, as the characteristics of these sources are relevant to all types of highway vehicles. Additional detail on the most significant of these noise sources is presented in Appendix C.

Trucks

Gasoline engines power 97.5 percent of the trucks in operation, and the remaining 2.5 percent are powered by diesel engines. Diesel trucks are generally 8 to 10 dB noisier than gasoline powered trucks and 12 to 18 dB noisier than automobiles.[17,18] The noise output of trucks increases with age, and about 60 percent of operating trucks are more than 5 years old. This increase of noise with age is aggravated by the tendency to overhaul trucks with replacement mufflers or recapped tires which generate higher noise levels than the original equipment.

The major contributing subsources of truck noise include the exhaust, cooling fan, engine mechanical noise, intake noise and tire/roadway noise. Figure 2.4-6 and Table 2.4-1 depict the relative contribution of these subsources to overall noise levels, and Figure 2.4-6 presents a range of octave band spectra for typical operating modes.[19 - 21] Following is a discussion of each of these major subsources.[12-14, 16, 18, 22-32]

- Exhaust – The noise levels generated by truck exhaust systems are dependent on factors such as engine type, timing and valve duration, induction system, muffler type, muffler size and location in the exhaust system, pipe diameter, dual or single system, and engine back-pressure. The actual noise-generating mechanism is created by vibrating columns of gas at high pressure amplitudes which are produced by the opening of the exhaust valve. This noise is communicated directly to the atmosphere. Additional exhaust noise is created by the direct impingement of these released gases on the pipes and muffler shell. The fundamental and harmonics of engine firing frequency are the principal components of exhaust noise. At high engine

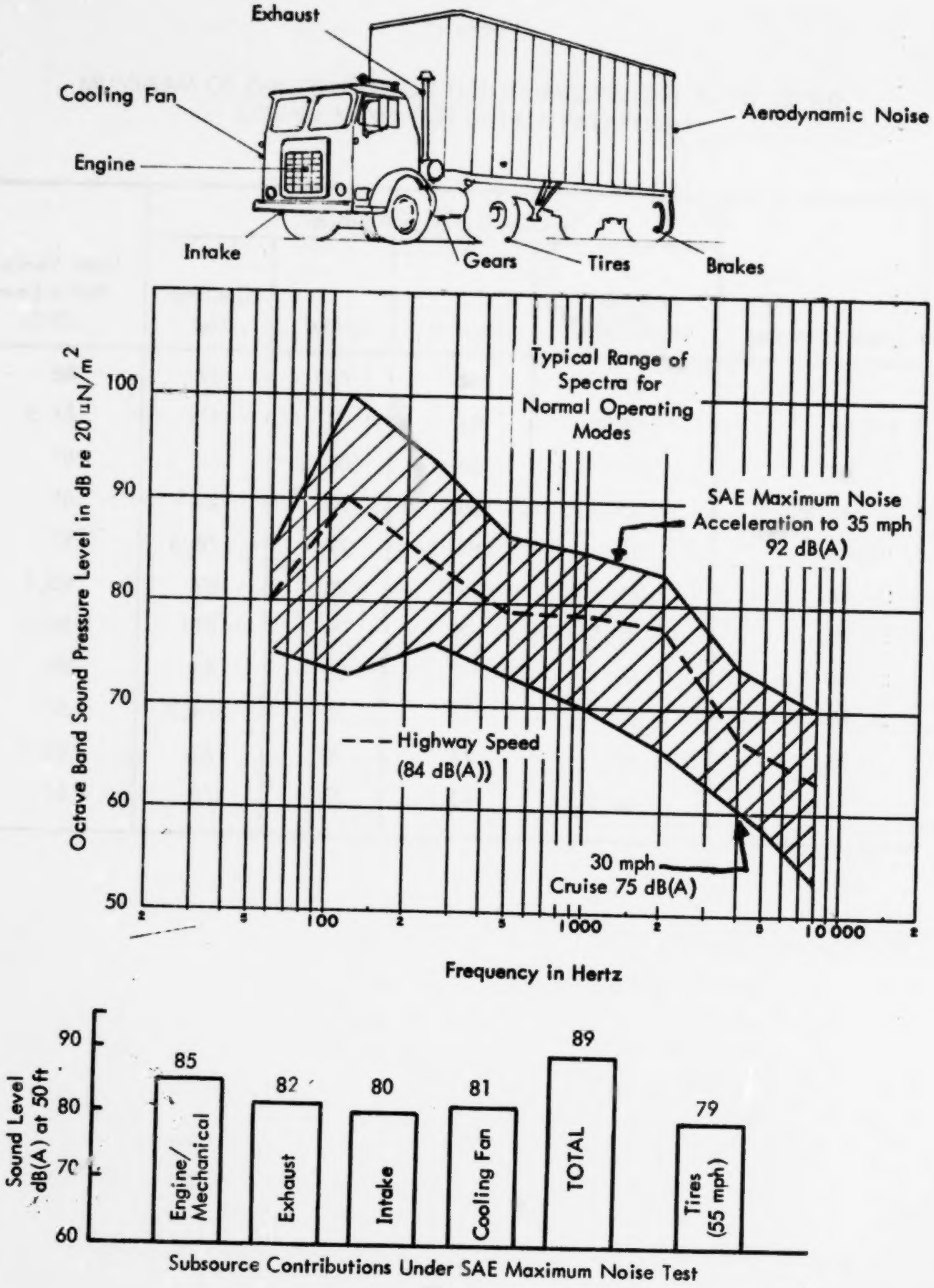


Figure 2.4-6. Typical Example of Diesel Truck Noise

Table 2.4-1

DIESEL TRUCK NOISE COMPONENT CONTRIBUTIONS TO MAXIMUM NOISE LEVELS AT 50 FEET FROM VEHICLE

Truck Examples	Contributing Subsource				Total Vehicle Noise Level dB(A)
	Engine Mechanical	Exhaust	Intake	Cooling Fan	
#1	81	84	75	82	88
#2	85.5	81	74	81	87.5
#3	83	86	80	81	89
#4	85	82	80	83	89
#5	83	83	72	78.5	87
#6	81	77	70	82	85.5
#7	82.5	86	79	82	89.5
#8	85	82	80	83	89
#9	83	83	72	78.5	87
#10	81	77	70	82	85.5
#11	83.5	82.5	74	78	87

speeds, these individual frequency components are masked by a more continuous spectrum created by the turbulence noise produced by the flow of high velocity gases through the exhaust valve.

- Cooling Fan – In nearly all applications involving water-cooled engines, an axial flow type fan is used to draw cooling air through a forward-mounted radiator. In many designs, fan noise approaches the level of exhaust system noise and is generally considered an important factor in reducing overall vehicle levels.

  Generally, fan noise is directly related to fan speed. It has been shown that fan noise increases at a rate of 2 dB per 100 rpm at speeds between 1000 and 1500 rpm and at a rate of 1 dB per 100 rpm between 1500 and 2000 rpm. The noise output is also dependent upon tip speed and configuration, blade design and spacing, and proximity of accessories and other objects which affect air flow.
- Intake – Induction system noise is created by the opening and closing of the inlet valve, starting and stopping the air flow into the cylinders. It is also markedly affected by the flow properties of the exhaust valve and the exhaust system due to the fact that during the duration of intake and exhaust valve overlap, some exhaust noise is transmitted through the intake. Intake noise of supercharged, blower-scavenged and turbocharged engines is created by the air-compressing process. It may be modified by resonant induction systems which can, under certain conditions of engine speed and system length, amplify intake noise levels. The intake noise increases with increasing load. For diesel engines between no-load and full-load, this increase may range from 10 to 15 dB, while gasoline engine intake noise may increase from 20 to 25 dB.
- Engine Noise – Engine-associated noise in internal combustion engines is produced by the compression and subsequent combustion process

which gives rise to severe gas forces on the pistons and to forces of mechanical origin, such as those produced by piston-crank operation, the valve-gear mechanism, and various auxiliaries and their drives. Both types of fluctuating forces produce mechanical vibrations of the engine structure which in turn cause all components attached to the engine to resonate and radiate noise.

As previously noted, diesel engines are typically about 10 dB noisier than gasoline engines. This difference results mainly from their different mechanisms of ignition. Gasoline engines initiate combustion with a spark from which the flame front gradually spreads throughout the combustion chamber until the entire fuel/air charge is burnt. This yields a smooth blending with the compression. The diesel engine, however, relies on a much higher compression ratio to produce spontaneous combustion which burns a large volume of fuel/air mixture rapidly. This yields a much more severe and more rapid pressure rise in the cylinder, causing more engine vibration for the diesel engine in comparison with the gasoline engine.

Many efforts at quieting diesel engines are aimed at smoothing out this abrupt pressure rise, either through prechamber combustion chamber designs or turbocharging (which tends to reduce these abrupt pressure rises). However, efforts at reducing diesel engine noise by smoothing out cylinder pressure rises are only effective when combustion-excited noise is greater than mechanical noise.

At constant speed, diesel engines show only slight reduction in noise, with reduction in load due to the high compression pressure even under no-load. Gasoline engines, however, show a substantial decrease in noise output with decreasing load, due to throttling of the inlet which yields a large reduction of compression pressure. Therefore, the change in noise level between no-load and full-load conditions is rarely more than 3 dB for a diesel engine, but can be as high as 10 dB for gasoline engines. In addition, compression ignition in diesel engines produces their characteristic "knock" which is associated with a broad peak of noise in the frequency range from 800 to 2000 Hz. Engine speed also affects engine noise output. At low speeds under full load, the gasoline engine is quieter than the diesel; however, the noise from gasoline engines increases much more rapidly with increasing engine speed than from diesels (45 dB per tenfold increase in engine speed versus 30 dB for diesels). Hence at high speed, the noise levels of both diesel and gasoline engines are of the same order of magnitude for the same horsepower.

- Tires – Truck tire noise presents the major obstacle in limiting overall vehicle noise at speeds above 50 mph, since at this speed tire noise often becomes the dominant noise-producing source on heavy duty trucks. Typical noise levels from truck tires at 50 mph range from 75 dB(A) for "low noise" tread designs to over 90 dB(A) for "high noise level" tires. Figure 2.4-7 illustrates the noise output of various truck tire tread configurations over the normal speed range of interest. The major offender is the standard cross-bar design used by the vast majority of trucks on their drive wheels. These tires may produce levels in the 80 to 85 dB(A) range when new, but their noise increases with wear as much as 10 dB in the half-worn condition. This increase is attributable to a change in the tread curvature resulting from wear. Cross-bar retreads pose an even greater problem as their noise level can be as much as 95 dB(A) at 50 feet when operated at 55 mph in the half-worn condition. Despite their noise, cross-bar retreads are very popular for economical reasons and each tire is recapped an average of two to three times. They wear roughly twice as long as the continual rib automobile type design tires and exhibit superior dry and wet traction performance.

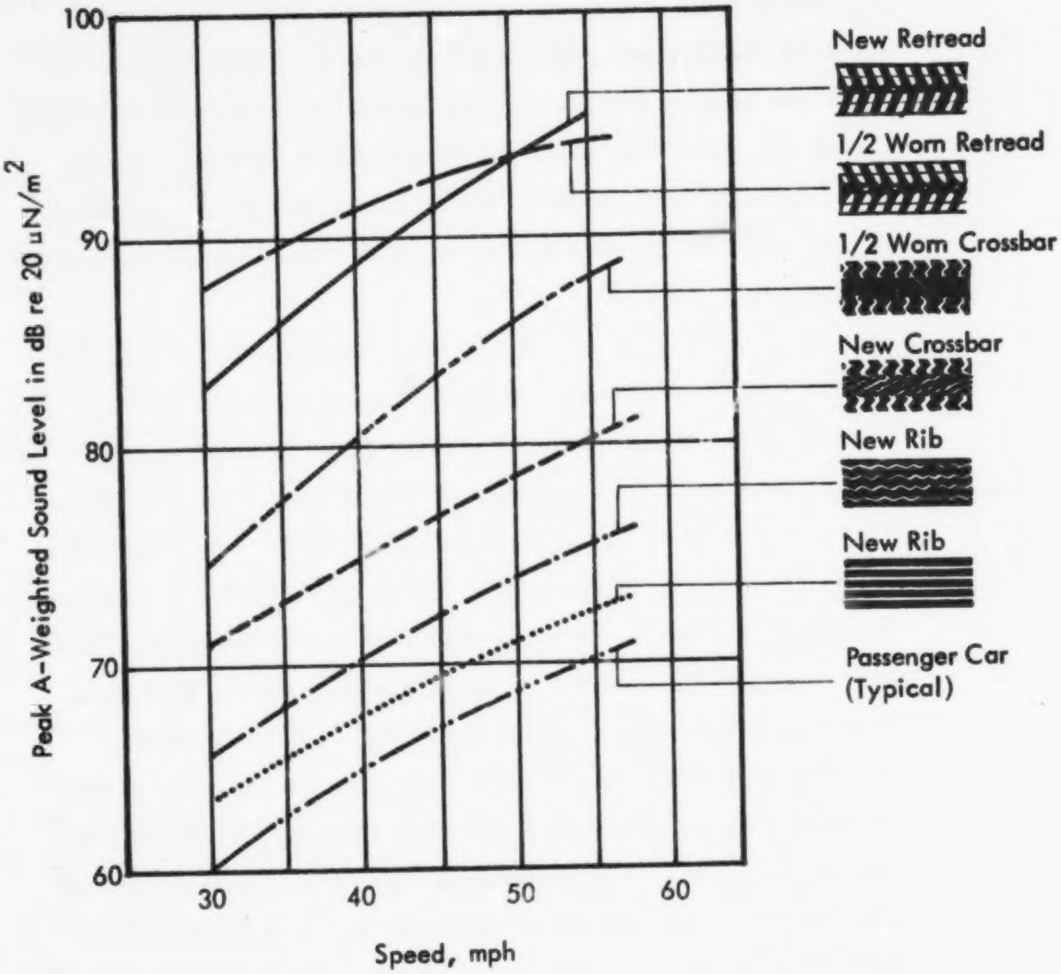


Figure 2.4-7. Effect of Various Tires Mounted on the Drive Axle. Loaded Single Chassis Vehicle Operating on Concrete Road Surface (Levels at 50 Feet)

Tire manufacturers state that recapped tires are generally much noisier than are new tires because of tread design. Current new tread designs are optimized on the basis of both traction and noise output. However, most recap tire molds are 5 years old or more and do not reflect the newer thinking in quiet tread designs such as randomized tread element size and spacing variations. These older molds become a critical noise factor when one considers that well over half the truck tires on the road today are retreads.

Axle loading is also a major factor in the amount of noise generated by tires. Retread tires exhibit the most predominant dependence upon load. One example indicates a decrease of 15 dB resulting when load per tire was reduced from 4500 to 1240 lbs. The explanation is that with the tire unloaded, the sides of the retread do not contact the road surface, hence the cups in the tread cannot seal against the road surface and compress small pockets of air.

New and half-worn cross-bar tires also produce more noise with increasing load. The explanation follows that with increasing load, the tread pattern is compressed, hence more of the load is carried on the outer sections of the tread.

The rib type tire designs are generally independent of loading due to their uniform tread design accross the tire cross-section.

Variations in road surface also significantly affect tire noise generation. Here again, retread tires exhibit the most dependence on this variable, with the most noise generated on smooth road surfaces. Differences have been observed experimentally to be of the order of 8 dB at speeds of 40 to 50 mph.

Automobiles

While not as noisy as trucks, buses and motorcycles, the total contribution of automobiles to the noise environment is significant due to the very large number in operation. Approximately 70 percent of automobiles on the road in 1970 were over 3 years old, the average age being about 5-1/2 years.[1] Vehicles over 2 years old tend to produce higher noise levels (2 to 3 dB) under most operating conditions, due to deterioration of exhaust silencer performance and the response of the vehicle to pavement roughness.[8] Like trucks, the noise produced by individual automobiles is a function of several subsource contributions – exhaust, cooling fan, intake, tires, engine and transmission noise and aerodynamic noise.

Figure 2.4-8 illustrates the relative contributions of these major subsources of noise to the overall noise levels and shows typical octave band spectra for various automobile operating modes.[6,24,33] Following is a discussion of each of these subsources.[12-14,21,24,34-36]

- Exhaust – For most automobiles, exhaust noise constitutes the predominant noise source for normal operation at speeds below about 35 to 45 mph, depending upon the condition and design of the exhaust system. Above this speed range, in many cases tire noise becomes equally significant. While exhaust noise does not create a significant interior noise problem, certain objectionable periodic tones may be audible inside the car.
- Intake – Intake noise in automobiles constitutes a minor problem in achieving current and projected automobile noise requirements, and the noise control principles are well understood by automotive engineers. Underhood space is sufficient to allow air cleaners large enough to achieve adequate silencing with minimal air restriction.
- Fan Noise – In some cases, the intensity of fan noise is almost equal with exhaust noise. The parameters which govern fan noise generation are essentially the same as those related to trucks. More work has been done in the passenger car area to reduce noise in the passenger compartment, hence quiet fans have been desirable for some time.

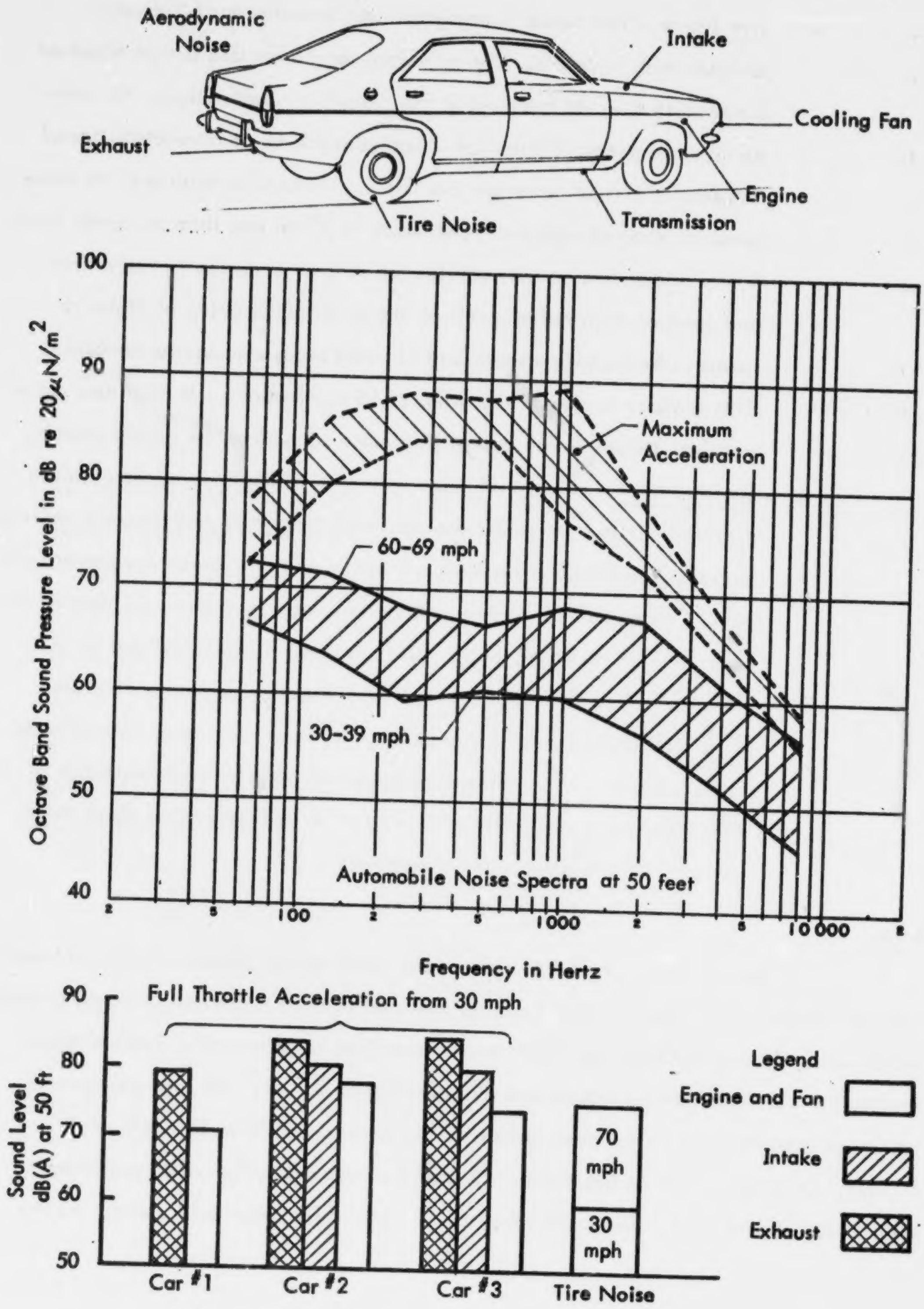


Figure 2.4-8. Typical Examples of Automobile Noise

- Tire Noise – Tire noise in passenger cars presents much less of a problem than in trucks. The principal reason for this is that standard automobile tires do not employ the cross-bar tread design. For comparative purposes, Figure 2.4-7 includes the noise characteristics of a typical rib-type passenger car tire. As can be observed, its noise level at 50 to 60 mph can be as much as 25 dB less than the worst truck tires. Snow tires on automobiles are similar in design to truck tires and produce high noise levels on the order of 85 dB(A) at highway speeds. At highway speeds and at rated load, current automobile tires produce levels on the order of 65 to 75 dB(A). In most new automobiles, these are the controlling noise sources at the higher speeds.
- Engine Noise – Nearly all passenger cars utilize four-cycle gasoline powered engines which for the most part (imported and compact vehicles excepted) normally operate at a fraction of their rated horsepower output. Consequently, engine mechanical noise is a minor problem to the observer. In addition, automobile engines are well shielded on all sides; therefore little noise is radiated directly out to the observer. Most attention to engine/transmission noise is focused on reduction of interior noise levels. Extensive noise attenuation treatment work is conducted on the majority of U.S. cars to reduce engine noise transmission into the passenger compartment.

Buses

Although trucks and buses share many basic design characteristics and some common components, buses are generally quieter due to their increased packaging space, which allows larger mufflers, and their enclosed engine compartment. Typical noise spectra for buses at highway speeds are shown in Figure 2.4-9.[6] At highway speeds, passenger buses exhibit noise levels primarily in the range of 80 to 87 dB(A) at 50 feet,[6] principally due to tire noise. One of the most annoying noises produced by city buses is heard by the person standing at the curb while a bus pulls away. As the

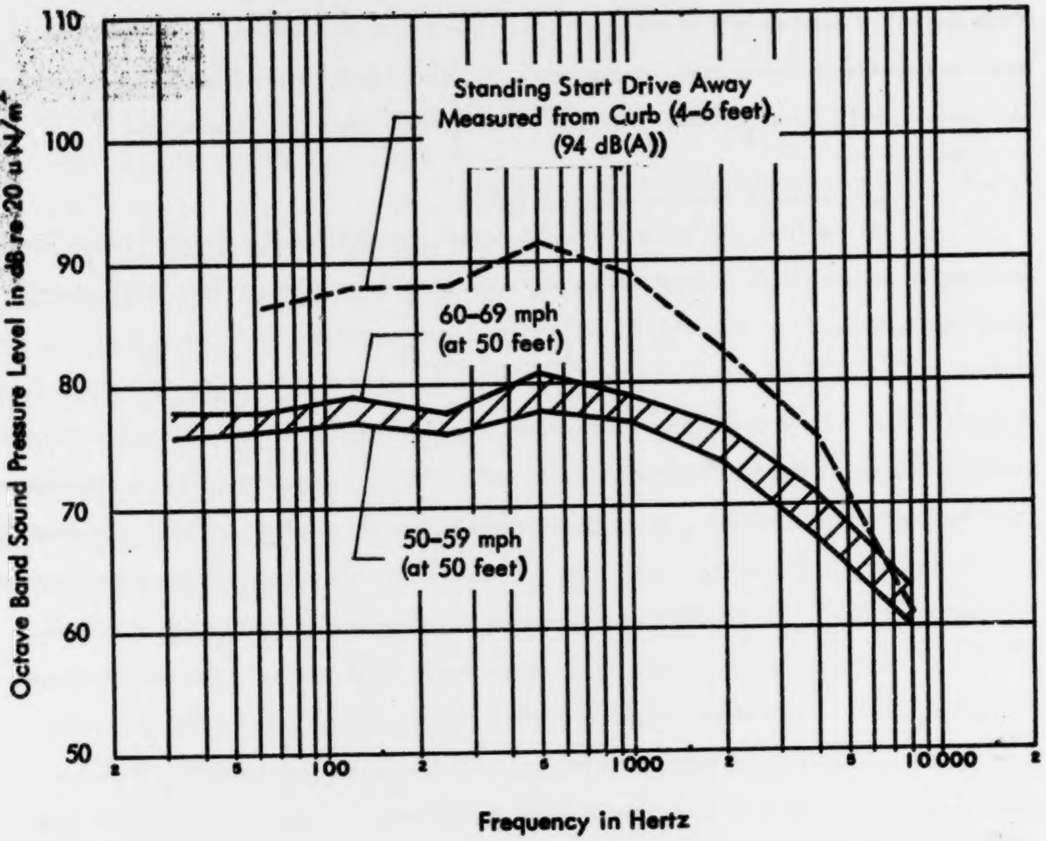

Octave Band Sound Pressure Level in dB re 20 u N/m^2
110
100
90
80
70
60
50
2
5
100
2
5
1000
2
5
10 000
2
Frequency in Hertz
Standing Start Drive Away
Measured from Curb (4–6 feet)
(94 dB(A))
60–69 mph
(at 50 feet)
50–59 mph
(at 50 feet)

Figure 2.4-9. Typical Octave Band Spectra for Highway Buses

bus passes the person, its noise level increases until it reaches a maximum of well above 90 dB(A) as the engine intake grille passes. This noise has a startling effect because of its sudden onset and very high level.[37]

Utility and Maintenance Vehicles

Utility and maintenance vehicles share many common elements with trucks. The chassis elements are essentially identical to heavy and medium trucks, hence the noise output at most speeds is quite similar. The major distinction lies in the type of auxiliary functions these vehicles perform. A typical octave band spectra is presented in Figure 2.4-10 for a garbage compactor during the compacting operation.[38]

2.4.3 Environmental Noise Characteristics

Noise from vehicular traffic generally establishes the residual noise levels (defined in Section 2.1) in most urban and suburban communities. This residual noise level varies throughout the day, based on the average density of noise sources in a given community.[39] In the immediate vicinity of a major arterial or freeway, the noise level is much higher. Its actual value is dependent upon traffic flow rate, average vehicle speed, distance to the traffic lane and the ratio of trucks to automobiles on the highway. For a typical 4-lane freeway, average daytime traffic flow rates can be of the order of 6 to 10 thousand vehicles per hour. For this condition, the median noise level beyond 100 feet from the flowing traffic is equivalent to a continuous line of noise sources.

Under this condition, the average noise level varies in the manner shown in Figure 2.4-11. This level increases 3 dB for every doubling of traffic flow rate, 6 dB for every doubling of vehicle velocity, and decreases approximately 3 dB for every doubling of distance from the freeway centerline.[10] At distances of the order of 500 to 1000 feet from the freeway, the decrease in noise level with distance generally ceases, as the freeway traffic noise becomes equal to ambient level in the neighborhood.

Superimposed on this median traffic noise level are the intrusive or single-event noises from individual noisy trucks, cars and motorcycles. These are normally

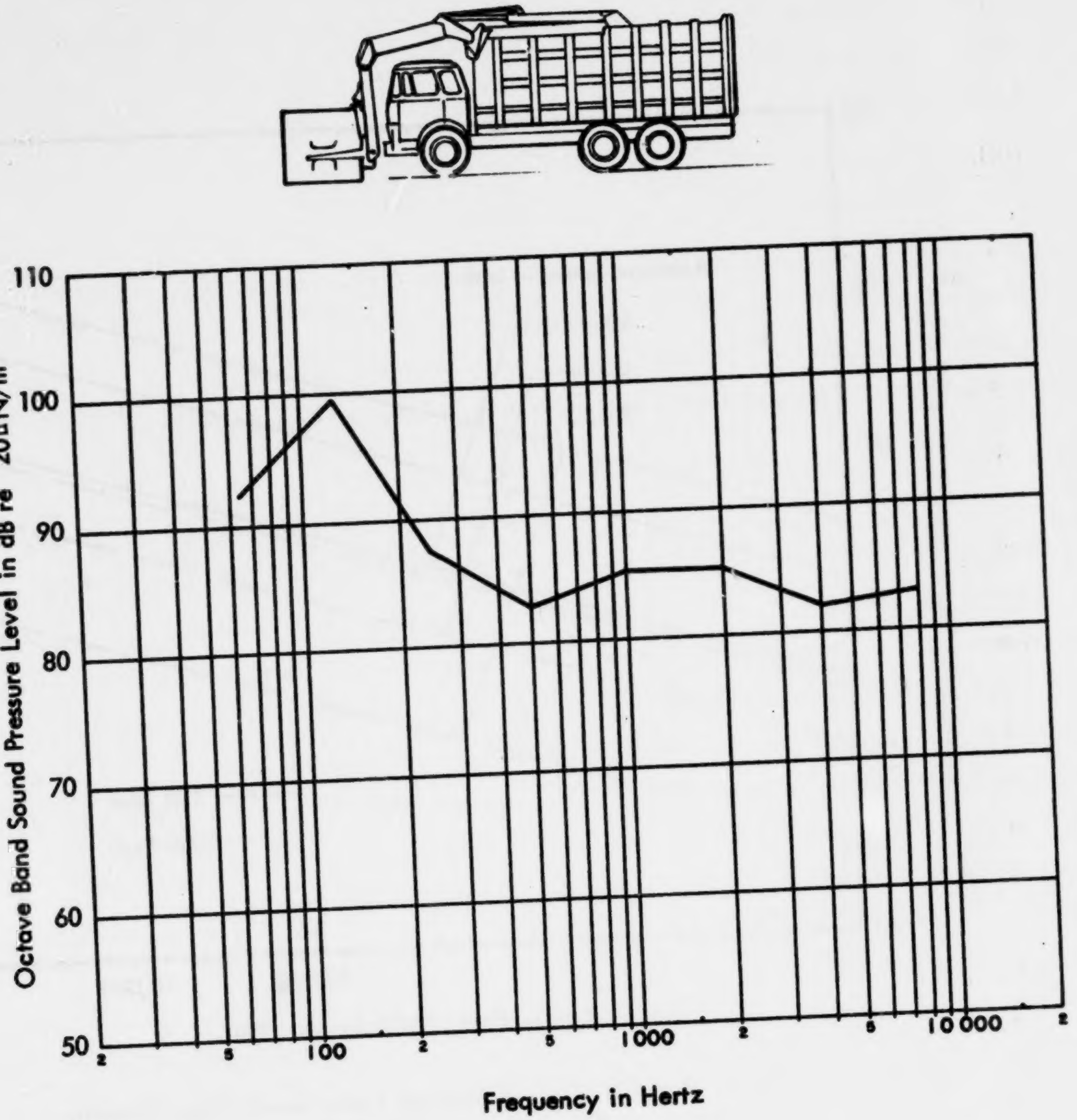


Figure 2.4-10. Typical Octave Band Spectra for Garbage Compactor During Compacting Operations (Levels at 50 Feet)

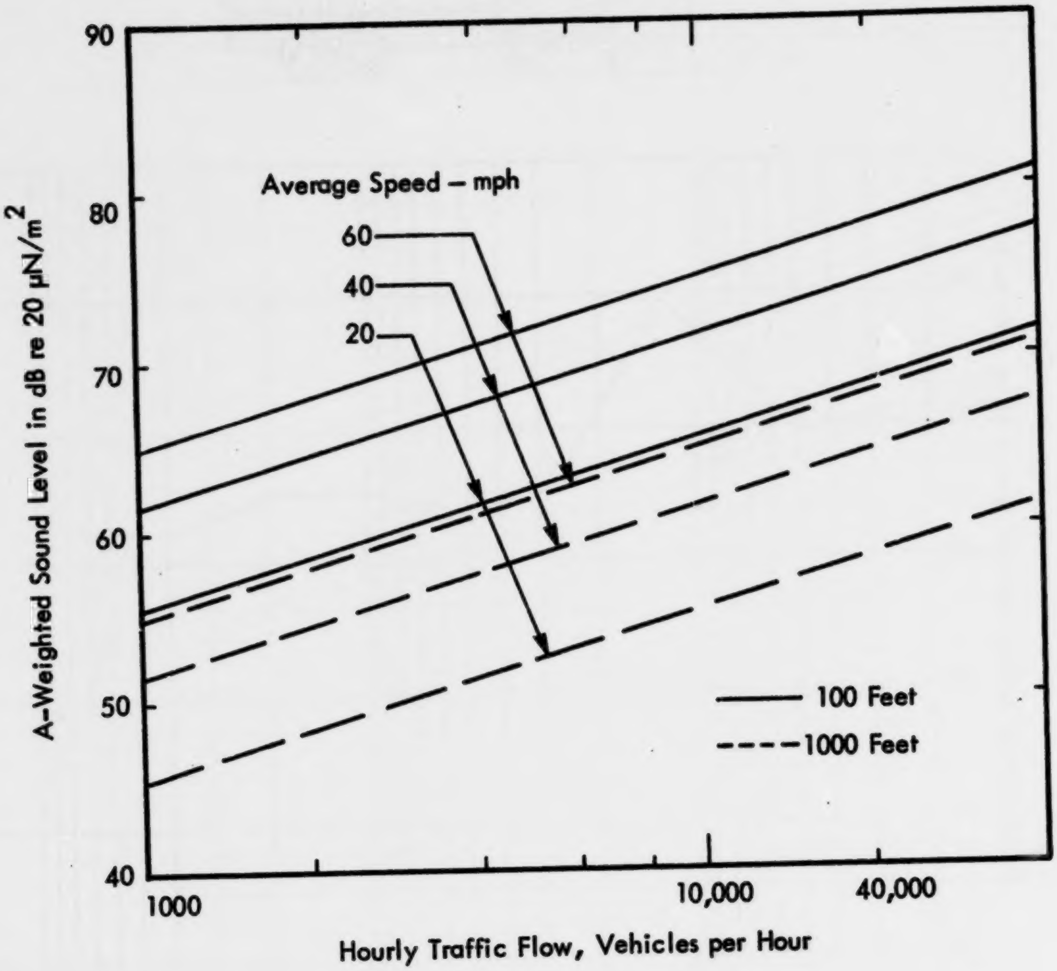


Figure 2.4-11. Typical Average Noise Levels Near Freeway (Diesel Trucks < 3% of Total)

15 to 25 dB above the residual noise levels on neighborhood streets. However, at the high traffic flow rates typical for freeways, these individual single events are barely distinguishable from the overall roar of the total traffic flow. During nighttime hours on major interstate freeways, the percentage of trucks is often much higher than on typical freeway systems, and truck noise dominates the traffic noise levels.

In a rural or "quiet" suburban community located well away from major highways, the normal ambient is 10 to 15 dB lower than in urban areas, and the passby of a noisy car will momentarily increase the noise level by as much as 40 dB above the ambient (L_{90}).[39] A noise intrusion of similar magnitude can also be created by garbage compactors and street sweepers that begin their rounds at 6:00 a.m.

Interior Noise Levels

Because most noise reduction in current automobiles has been created for passenger comfort, a special discussion is warranted on the subject of interior noise levels. Figure 2.4-12 shows a representative range of automobile interior noise spectra at highway speeds.[40, 41] At the upper end of the range is a popular import, while the lower end represents a medium-size standard domestic passenger car. The noise levels in the smaller import tend to be higher because of less sound treatment in the body, less resilient tires, and stiffer suspension systems.

Generally, the interior noise levels increase with speed, with the noise of domestic passenger cars increasing at about 2.5 dB per 10 mph, while the noise in sports cars and small imports increases at a higher rate – up to 5 dB per 10 mph. At 35 mph on an asphalt road, the typical interior noise levels range from 64 to 73 dB(A). Typical noise levels at 60 mph inside automobiles at highway speeds range from 63 to 82 dB(A) on concrete with windows closed. Air conditioners add at least 5 dB to the overall interior noise level, depending on operating mode and vehicle speed.[40, 42, 43]

Open windows generally increase noise levels 5 to 15 dB, depending on the "closed window" noise level, aerodynamic design and the combination of windows which are opened. A particularly annoying Helmholtz resonant condition can be created in some vehicles by opening just one side window. Noise levels at this

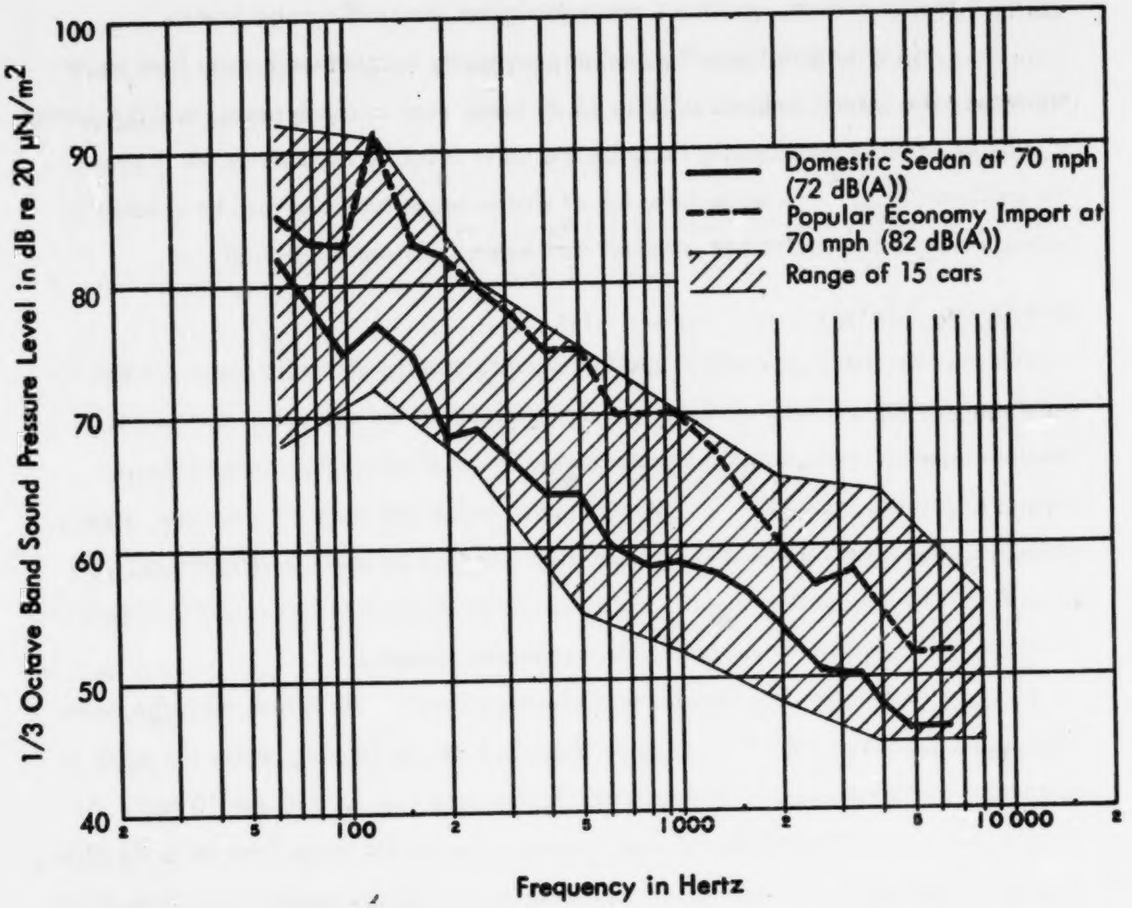


Figure 2.4-12. Range of Typical Interior Noise Levels for Domestic and Imported Passenger Cars at Highway Speeds

resonance may be well in excess of 100 dB(A). This resonance usually occurs at a specific speed and often may be stopped by opening an opposite window a very small amount.[40]

Buses, by virtue of their rear engine design and adequate allowance for interior sound package treatment, provide generally acceptable interior noise levels in the range of 72 to 80 dB(A). However, the interior noise in trucks ranges up to 100 dB(A) for the largest and noisiest trucks. These higher levels may be excessive in terms of a potential hazzard of hearing loss.

2.4.4 Industry Efforts Toward Noise Reduction

The highway vehicle industry is strongly committed to the development of vehicles intended for specific segments of the consumer public. Each vehicle model is manufactured with a particular performance goal or overall image in mind. This image ranges from a luxury vehicle, wherein a quiet car is desired by the consumer, to a performance vehicle which generally exhibits as high a noise level as is legally allowed to provide the consumer with a sense of power. Considerable technical effort has been expended for many years to obtain the "proper sound" for each automobile design.

At its infancy in the early 1900's, the automotive industry found it necessary to equip its engines with mufflers when the noise of the "horseless carriage" frightened horses on the road. Cities and towns began to require mufflers on cars in the 1920's and the automobile muffler has improved significantly since that time.

Trucks, utility and maintenance vehicles, and buses are generally manufactured to individual customer specifications which place major emphasis on performance, operating economy and initial cost. The customers in this industry often associate noise with better economy and more power; hence there has been little customer pressure to reduce truck noise, although individual cities and towns have begun to demand quieter maintenance vehicles and buses. In the late 1950's, recognition that exterior truck noise was causing problems led the Society of Automotive Engineers (SAE) to develop a truck noise measurement standard and to recommend a maximum exterior loudness level of 125 sones at 50 feet. This standard, including the recommended maximum level, was voluntarily adopted by the major producers of trucks and resulted in a reduction in the noise of the larger trucks. More recently, this standard has formed the basis for the measurement of truck noise by new state legislation and regulations. The manufacturers are committed to meet the exterior noise goals of this new state noise legislation. However, the accomplishment of this commitment is greatly complicated by the fact that the new vehicle manufacturer faces a number of differing noise laws and measurement standards throughout the country, and different time deadlines for achieving various amounts of noise reduction. In general, manufacturers have been faced with very short time constraints and have been essentially forced to exploit the "band-aid" type of problem solution, without having adequate time to incorporate the new requirements into a basic redesign. This approach is generally wasteful of effort and costly to the consumer. It is preferable for the manufacturer to have a single set of regulations which are technically and economically achievable and which contain a time schedule compatible with the basic design, prototype, test and production tooling timeframe. This approach generally will achieve the best overall design in respect to both vehicle performance and ultimate cost to the consumer.

An additional factor which influences the industry commitment is pending legislation in other areas of concern to manufacturers which include safety, emissions and, of late in the trucking industry, horsepower/ton considerations which may greatly affect powerplant and chassis designs.

The industry employs qualified noise control engineers who have extensive experience in solving all types of vehicle noise problems to satisfy market requirements. They are geared to solve problems in new models within very tight schedule constraints prior to start of production. Many companies incorporate large noise control staffs which have at their disposal sophisticated laboratory facilities and computer assisted analysis equipment. The analyses are highly refined and are geared toward problem area definition and comparison of relative improvements in problem areas.

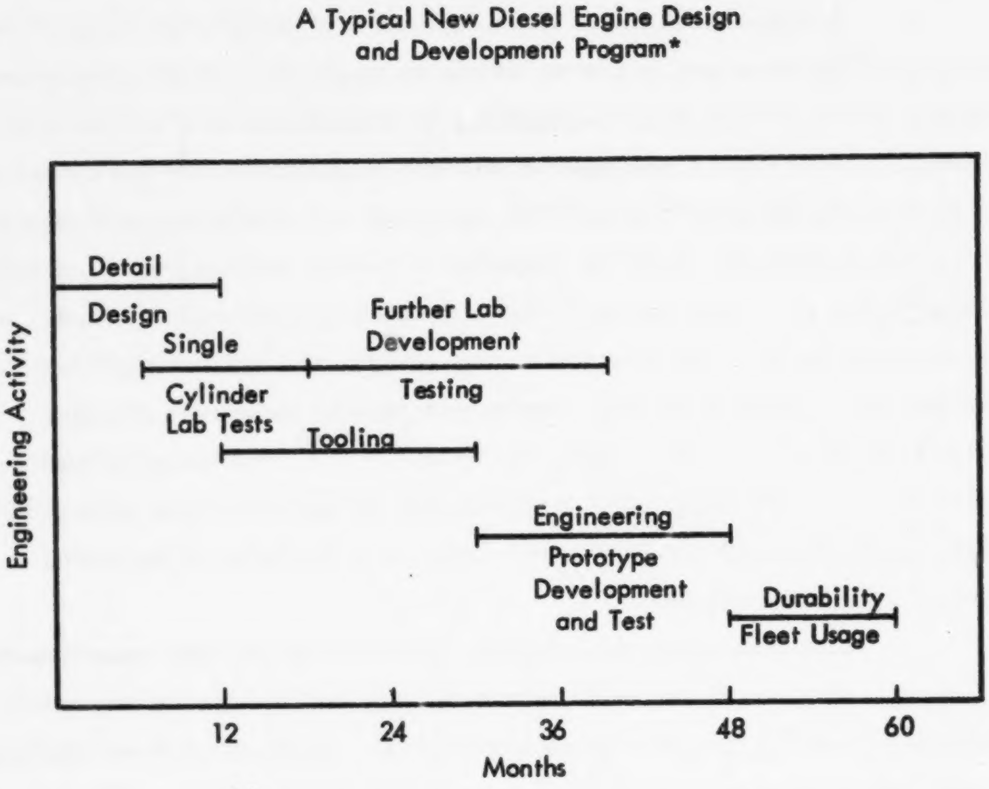
Though most of the principles of noise generation in highway vehicles are well understood, incorporation of advanced acoustic technology proceeds slowly for a number of reasons, the foremost being that the engineers are almost always dealing with a basic design which is in production. Any new refinement to a specific model may require modification to the original basic design and must be compatible with all design and production constraints.

A further consideration in the application of acoustic technology is that a majority of the components in a motor vehicle are supplied by outside specialty product vendors who do not have direct responsibility for the performance of the total end product. The net result of this aspect is that many manufacturers are now compelled to supervise the design of these auxiliary components or to produce many of them to insure that the total system will be compatible in terms of function and desired acoustical performance. A good example of this is the cooling system on heavy trucks, wherein the entire cooling system must now be engineered by the vehicle manufacturer to achieve adequate engine cooling, together with reduced transmission of engine mechanical noise and reduced cooling fan noise.[24,25,44] The increased requirements for system design which tend to exceed the technical scope and capability of the specialist vendors may lead to major changes in the historical purchasing pattern of the entire industry.

One final aspect which impedes application of advanced acoustic technology is the high use factor associated with highway vehicles and the very severe economic/durability constraints on the manufacturer. Extensive and time-consuming highway durability test programs always precede introduction of any modifications to today's vehicles, as illustrated by the typical engineering/development/production timing schedule shown in Figure 2.4-13.[44]

2.4.5 Noise Reduction Potential

Figure 2.4-14 illustrates the present ranges of noise levels for highway vehicles under both maximum noise conditions (SAE test method) and highway cruise conditions. It summarizes noise reduction potentials deemed achievable in the near



A Typical New Diesel Engine Design and Development Program*

*Based essentially on minor modifications (such as displacement increase) of an existing engine series.

Figure 2.4-13. Typical Industry Production/Timing Schedule

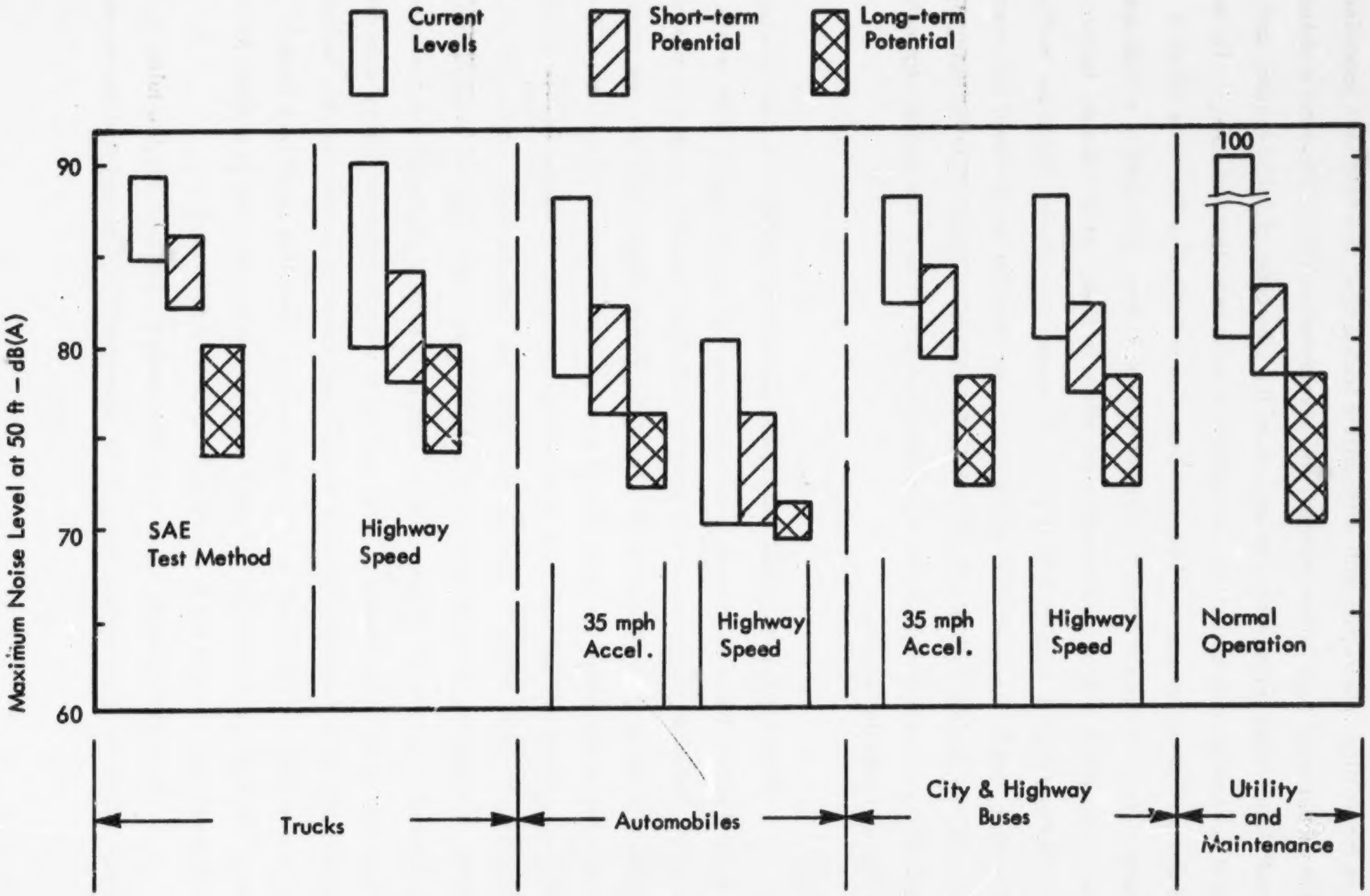


Figure 2.4-14. Effect of Potential Noise Reduction for Highway Vehicles

future for existing vehicle concepts with current technology, and long term potentials which should result from further research and development efforts. These noise reduction potentials are based on an extensive analysis of the subsources of vehicle noise, and assume continuing advancement in the applicable noise reduction technology. For most vehicles at highway speeds, the long term potential is limited by tire noise which is inadequately understood at present. Further noise reduction, particularly at high speeds, requires successful research and development efforts in tires. At low speeds, further reduction may require considerable effort in advancement in engine design and muffler technology, and for large vehicles possibly a change from the conventional reciprocating engine to new devices such as the gas turbine for propulsive power. The following paragraphs discuss current and projected noise reduction activities of the various segments of the highway vehicle industry.

Trucks

Historically, many new trucks were sold without mufflers in their exhaust system and with little or no attempt to minimize cooling fan and engine noise levels. Such noise reduction simply was not in keeping with the customer's request for maximum performance and economy of operation. However, heavy diesel trucks are now recognized as the loudest single category of highway vehicles. A recent statistical study on traffic noise shows the average noise level at highway speeds of tractor trailers to fall in the 85 to 90 dB(A) range.[6] Considerable effort has been expended on the part of industry in attempting to quiet these machines. One particular program currently underway involves a joint effort between the California Division of Highways and the International Harvester Corporation.[44] Their goal is to silence a standard heavy-duty diesel-powered vehicle as much as is feasible through application of current acoustic technology. Their stated goal is 83 dB(A) at 50 feet, but they are attempting to achieve lower levels. While program costs are not available, the project has been in progress for the past 6 months and is expected to continue for another 3 to 6 months.

The average heavy diesel truck will probably run over 500,000 miles in its lifetime. Over this time period, many of the components will be replaced due to wear or be modified to meet individual operator needs. The net result of this long-term usage is that after a year or two, the noise characteristics of many heavy trucks is altered significantly. The widespread usage of retread tires and modified exhaust systems contribute to even higher overall truck levels.[13,35]

Figure 2.4-15 illustrates the potential noise reduction of the major sub-sources of truck noise. The potential for reduction of noise generated by these sub-sources is discussed below.[12-14, 16, 18, 22-24, 27, 29-31, 33, 44-47]

- Exhaust System — In achieving reductions in the noise produced by heavy trucks, a foremost consideration must be the exhaust system. The effect of adequate exhaust silencing treatment alone, under maximum noise output conditions, can provide a gross overall noise reduction of at least 10 to 15 dB, bringing the over 100 dB(A) unmuffled offenders down to the 90 dB(A) range. It is considered that a feasible goal for the near-term in exhaust noise for all trucks appears to be in the range of 80 dB(A) measured at 50 feet. (In some instances a power loss may result.)
  The current state-of-the-art in muffler technology, which relies on large muffler volumes to obtain adequate silencing with low back-pressures, will allow approximately 18 to 20 dB attenuation through a muffler alone. When greater reduction values are sought, noise radiation from the pipe and muffler casing becomes a significant factor. In one program, where greater exhaust noise reduction was required, the exhaust pipe diameter was reduced from 4 inches to 3-1/2 inches, yielding a noise reduction of the order of 25 dB with a typical diesel engine and muffler. This reduction in diameter, however, could lead to an increase in back-pressure of approximately 40 percent. Some turbo-charged diesel engines (exhaust turbine-driven supercharger) may meet current legal noise restrictions without the use of mufflers. These devices, like mufflers, extract energy

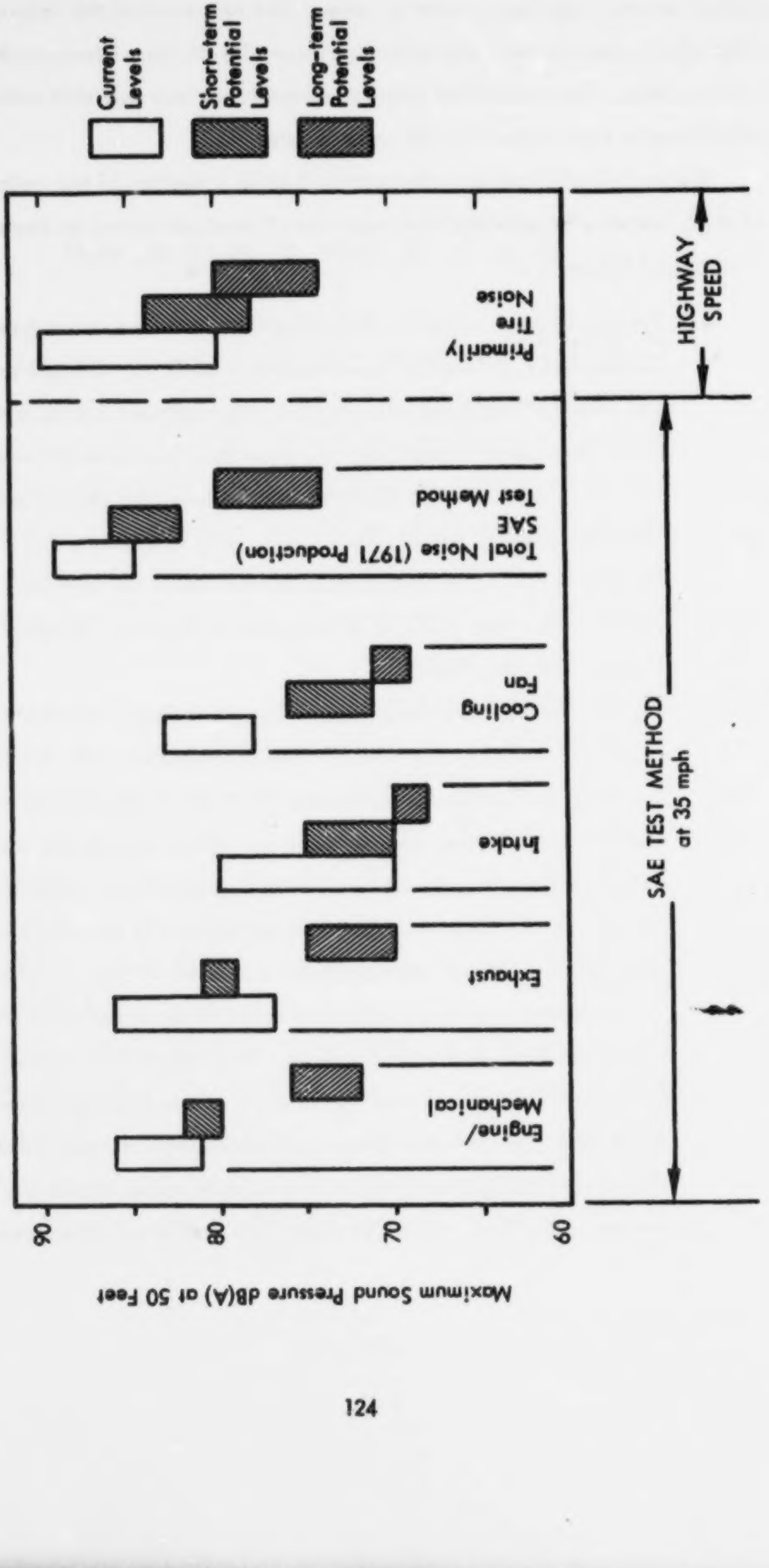


Figure 2.4-15. Effect of Potential Noise Reduction for Diesel Trucks

from the stream of exhaust gases. Further research into exhaust system designs, or allowance for more muffler space in new truck designs, could produce additional exhaust noise reduction for future vehicles without drastically increasing engine back-pressure, although in the interim some increased back-pressure and the associated power loss may have to be accepted to achieve significantly reduced levels. It would appear that exhaust levels in the 70 to 75 dB(A) range should be feasible in the longer term.

- Cooling Fan – The standard method of reducing fan noise is to utilize a larger fan running at a slower speed to produce essentially the same air flow. In many cases, this solution necessitates a larger radiator at a definite cost and weight penalty. The extent to which this technique may be applied is, of course, limited by the overall radiator size which is of concern for driver visibility. Thermostatically-controlled fan release clutches are also successful in greatly reducing fan noise, but are only effective at highway cruising speeds where a sufficient cooling air flow is provided by the vehicle speed.

  A major consideration in the design of engine cooling fan systems is to minimize the horsepower requirements of the fan itself, which consumes from 5 to 11 percent of total engine horsepower. Larger fans, or increased cooling capacity requirements resulting from application of engine shielding and enclosure will have a marked effect on fan horsepower losses and hence performance and economy.

  Substantial development is required in the area of total engine system cooling and related heat transfer in order to provide a more refined solution to this problem. Acoustic technology for reduction of fan noise developed for the noise control of aircraft can be implemented; however, additional applied research and experimentation will be required before estimates of expected performance are possible.

Certain manufacturers are now instituting internal research activities aimed at development of new concepts in engine cooling. Based on analysis of existing programs, fan noise levels in the low 70 dB(A) range are a reasonable future expectation for low speed truck operation.

- Intake – Silencers are readily available which achieve reduced levels by utilization of a design which incorporates an expansion or plenum chamber to reflect noise back toward the engine. The amount of silencing achieved by these devices is a function of air cleaner size and location in the induction system, the optimum being the center of the air intake system. The frequency range of attenuation generally depends on location and air cleaner length; larger air cleaners attenuate lower frequencies. The most effective air cleaner/silencer designs currently available utilize an absorbent packed construction for high frequency absorption and incorporate a Helmholtz resonator into their designs for attenuation of frequencies below 600 Hz. Feasible near-term potential for intake noise levels fall in the 70 to 75 dB(A) range.

  The major considerations in implementing these designs are packaging the silencer and minimizing the amount of performance loss due to increased restriction in air flow. One manufacturer suggests that approximately 2.5, 3 and 8 percent power losses result from each additional inch of mercury restriction for two-cycle blower scavenged diesel, four-cycle naturally aspirated diesel and gasoline engines, respectively. It is believed that further overall engine development in this area will aid in reducing intake contribution to the 68 to 70 dB(A) range in the long term.

- Engine Noise – Reducing the total mechanical and engine-generated noise output is a critical problem facing truck manufacturers. Most current efforts by U.S. industry in reducing engine noise have involved acoustic shielding and encapsulation of the engine and transmission. These methods have met with little success, primarily due to engine cooling problems and increased servicing costs. Reduction in the diesel engine mechanical noise output appears limited to the general range of 81 to 84 dB(A) measured at 50 feet (see Table 2.4-1). Further, the current trend in engine design is to make power plants lighter and to extract more power; this exaggerates the noise problem.

Substantial research has been conducted by Priede in England on the subject of engine design. His work has established that by certain radical changes in design of the engine structure, engine noise levels can be reduced by 10 dB. The effect of these changes has been demonstrated in a research engine with resultant 7 to 8 dB noise reduction. The techniques involved adding more crankshaft main bearings to reduce crank vibration amplitudes and stiffen the engine structure, reducing maximum combustion pressure, closer tolerance to reduce piston slap and remounting accessories on the cylinder head (because of its stiffness, the cylinder head exhibits low vibration amplitudes and hence transmits little vibratory energy to accessories). In addition, all valve covers and engine cover plates were heavily damped and an isolated crankshaft pulley was used which incorporated damping rubber between the hub and rim to reduce noise radiation. The American manufacturers generally support Priede's work, but feel at the present time these techniques are only minimally effective and are presently impractical from cost and servicing standpoints. The basic problem in implementing these concepts is one of proving durability.

The research efforts of Priede and others could be the basis for a long-term goal in engine noise levels to be in the 72 to 76 dB(A) range (based on reduction levels achieved with experimental engines). The combined result of these noise reduction efforts for all component sources is a potential reduction of total truck noise, measured under current SAE maximum noise tests at 50 feet, to the 74 to 80 dB(A) range in the longer term.

A consideration in assessing long-term goals for truck noise reduction lies in the realm of incorporating power plants other than conventional reciprocating internal combustion engines. Much effort has been expended on the part of industry in attempting to utilize the gas turbine engine effectively in heavy duty truck applications. The technology exists for quieting turbine engines to a high degree of efficiency, although widespread application of turbines in the next 10 years is not anticipated unless significant breakthroughs in certain key design areas occur. However, the gas turbine may eventually provide a major breakthrough in truck engine noise reduction.

- Tires – At speeds greater than 45 to 50 mph, total truck noise levels are affected by tire noise. Obviously (from Figure 2.2.4-7), one way to reduce these levels is to outlaw the present design cross-bar design tires and not allow retreads of this design. This action would probably reduce truck tire noise levels at highway speeds by as much as 12 to 15 dB. However, as the cross-bar tires exhibit superior wear and traction characteristics over the alternative automobile-type rib tire designs, this change might have a significant impact on operating cost and safety. Therefore, it is reasonable to assume that current levels reflect the maximum reduction that can be achieved within economical and safety constraints with current technology. Further research into tire noise generation and the parameters of tire design is needed to achieve levels of 74 to 76 dB(A) at highway speed. In addition, as has been pointed out in Section 2, tire/roadway noise is greatly influenced by pavement surface characteristics; consequently, the burden of reducing tire noise levels should be studied jointly by the tire manufacturers and those responsible for highway design.

Automobiles

Substantial noise reduction is currently incorporated into the majority of automobiles. Much of this noise reduction is directed at reducing interior noise levels, and successful industry efforts have been rewarded by increased sales of those vehicles which emphasize quiet ride and passenger comfort. One automobile manufacturer has advertised that –

> "In the last 5 years, the noise level in American cities has risen over 20 percent. In the last 5 years, sales of the very quiet (manufacturer's brand name) have risen over 160 percent."[48]

This passenger car model, and other American passenger cars in the $3000 and up category, typically exhibit interior noise levels at highway speeds on the order of 63 to 70 dB(A) with the windows up and the air-conditioner off. With the air-conditioner on, the levels are usually increased by at least 5 dB. The automotive engineers who develop air conditioning systems feel the customer associates air conditioning fan noise with cooling – quiet air conditioning fans are not popular.

Studies of the exterior noise levels of passenger cars, measured under various normal operating conditions along freeways, city streets and rural roads, show the noise of the newest vehicles is slightly less than that of older vehicles. For example, a recent statistical study, conducted by the California Highway Patrol, obtained extensive noise data listed by manufacturer for models "1964 and earlier," and "1965 and later." In nearly all operational modes, the newer and older vehicles exhibited the same statistical average noise level for a given operational mode. Also, the vehicles of the various manufacturers exhibited identical average exterior levels. An exception were Volkswagens of "1965 and later" which were 1 dB noisier than the rest.[7] (Volkswagen represents 55 percent of all imports on the road.) Subsequent studies have been conducted which distinguish between "1968 and older" vehicles, and "1969 and newer." The newer cars in these studies average around 2 to 3 dB quieter than earlier models under most operational modes.[8]

Further silencing efforts in passenger cars, as in trucks, must be accomplished in the exhaust system. In general, incorporation of a dual muffler exhaust system will yield more noise reduction than the more economical single exhaust system. This is largely due to the principle relating exhaust silencing to muffler volume. Many current 1971 model passenger cars now produce levels approaching 80 dB(A) at 50 feet in the maximum noise tests when the test vehicle is fitted with a dual muffler system. For one manufacturer, this system raises the price of the car by an estimated $30.00 over that of a car with a single exhaust system.[33]

However, most major automobile manufacturers have stated that they will be incorporating catalytic conversion muffler systems to meet the 1975 emissions standards. It is anticipated that these systems will increase gas temperatures in the exhaust system by a significant amount in many applications and hence necessitate larger muffler volumes to achieve current noise levels. The use of the dual exhaust systems mentioned above will now become considerably more expensive due to the requirement of dual converters. Also, packaging of muffler units is a critical consideration in automobile design, and in most cases the addition of extra mufflers would necessitate redesign of the vehicle underbody. This change will undoubtedly also require the use of larger radiators, fan shrouding and larger fans. The net result will probably be a requirement for a great amount of effort to maintain current fan and exhaust noise levels.[24,33,34]

As has been stated earlier, under normal operating modes the automobile probably sets the majority of the ambient noise levels in communities. Hence, any major reduction in automobile noise will have a significant effect on the ambient noise environment. It would appear that levels around 68 to 70 dB(A) under cruise conditions at all legal speeds are potentially possible for automobiles. However, at 60 to 70 mph, the levels are highly influenced by tire noise, and hence cannot be achieved without further research and development. Thus, less potential noise reduction is anticipated at highway speeds in comparison with that expected for 35 mph maximum acceleration, as shown in Figure 2.4-14.

It is questionable whether or not the current SAE new car noise certification test for vehicle noise[49] is a totally reliable measure of automobile noise output, since a very small percentage of actual driving time is spent at full throttle acceleration. It is felt that to further reduce new vehicle noise levels, more attention must be paid their normal operating modes and future noise legislation must be geared in this direction.

Buses

Most noise reduction in buses has resulted from the desire to provide more passenger comfort. Buses utilize essentially the same propulsion systems as heavy trucks, but by virtue of their designs, which allow for larger mufflers, quieter tires and enclosed engines, are much less a noise problem.

As an example of silencing existing highway vehicles, a major manufacturer has developed a "retrofit" exhaust and noise emission reduction package for diesel-powered buses. The package includes modified fuel injectors and a large and rerouted exhaust muffler which now incorporates a reactor to provide further odor and emission control. In addition, the package includes a more effective air-cleaner/silencer unit and a modified engine mounting system which reduces noise by isolating the engine from the bus chassis. This system will provide up to 10 dB reduction in noise levels as well as providing significant reduction in exhaust emissions, smoke and odor. The cost of this conversion is $373.00 when installed on new coaches; however, to convert a used bus runs up to $1300.00 for materials, with an average of 160 manhours required for installation.[33,50,51] Clearly from this example, further effort into the area of developing economical "retrofit" noise reduction packages for long-life vehicles would appear to be feasible and warranted and not solely limited to bus applications but heavy trucks as well.

It is believed that further efforts toward aerodynamic styling will aid in reducing aerodynamic noise at highway speeds. Further reduction at highway speeds will be dependent upon newly-designed "quiet" tires. It is estimated that the noise at

50 feet from both city and highway buses can be reduced to levels of 74 to 76 dB(A) under both acceleration and highway speed conditions in the long term.

Utility and Maintenance Vehicles

Utility and maintenance vehicles are a breed apart from the rest of highway vehicle types. The only common elements are their chassis and propulsion systems. These vehicles are most often operated at low road speeds in lower gear ranges. As many of these vehicles are diesel powered, they tend as a group to produce high noise levels even at low speed. These vehicles are normally muffled, but little attention has been paid to noise associated with the auxiliary functions they perform.

Certain manufacturers have developed quiet utility vehicles and market them on a limited basis. One excellent example is the "quiet refuse truck" developed by General Motors for the State of New York. In addition to larger mufflers and a silenced air cleaner, numerous additional engine seals were utilized along with a "quiet" cooling fan and "quiet" tread tires. The refuse packer itself was quieted by isolating the hydraulic valves and lines, cushioning certain components and damping the body panels. Typical noise levels at 50 feet were reduced from approximately 87 dB(A) during the packing cycle to 80 dB(A). It is estimated that these modifications added about $3000 to the price of the complete unit.[33, 50, 51, 52]

Thus, auxiliary functions performed by these vehicles are amenable to noise reduction treatments. It is estimated that the refuse packing function can be reduced in noise level to the 76 to 78 dB(A) range in the medium to long term. The noise levels of street sweepers and other similar function vehicles should also be able to be reduced to a level of 70 to 75 dB(A) in the long term.

2.5 Rail Systems

2.5.1 Introduction

Rail systems are used for a variety of applications, including long distance freight and passenger trains, commuter trains and rapid transit trains. These applications have required development of specialized vehicle systems which differ significantly in their noise characteristics. In discussing the problem of noise in rail systems, it is convenient to consider the two following groups:[1-3]

- Railroads – including locomotive-propelled freight, long distance passenger and commuter trains, as well as high-speed intercity trains. This industry reported $12 billion in operating revenues in 1970, and employed 566 thousand trained personnel. Railroad passenger traffic has steadily declined during the past 20 years to a figure of 283 million passengers carried 11 billion revenue passenger miles in 1970, approximately one-third of those traveled in 1950. However, freight ton-miles have increased during this period from 590 billion to 776 billion. Manufacturers of railroad equipment made $2 billion worth of shipments and employed 50 thousand people in 1970.
- Rail Rapid Transit Systems – including subway and elevated systems, surface stretching railways and trolley lines. Intracity rail transit has declined since 1950 from 907 million to 480 million revenue passenger miles. This segment of the rail industry reported $1.7 billion in operating revenue for 1970 and employed 138 thousand trained personnel. This system transported approximately 2.1 billion passengers in 1970.

The characteristics of rail systems are summarized in Figure 2.5-1.

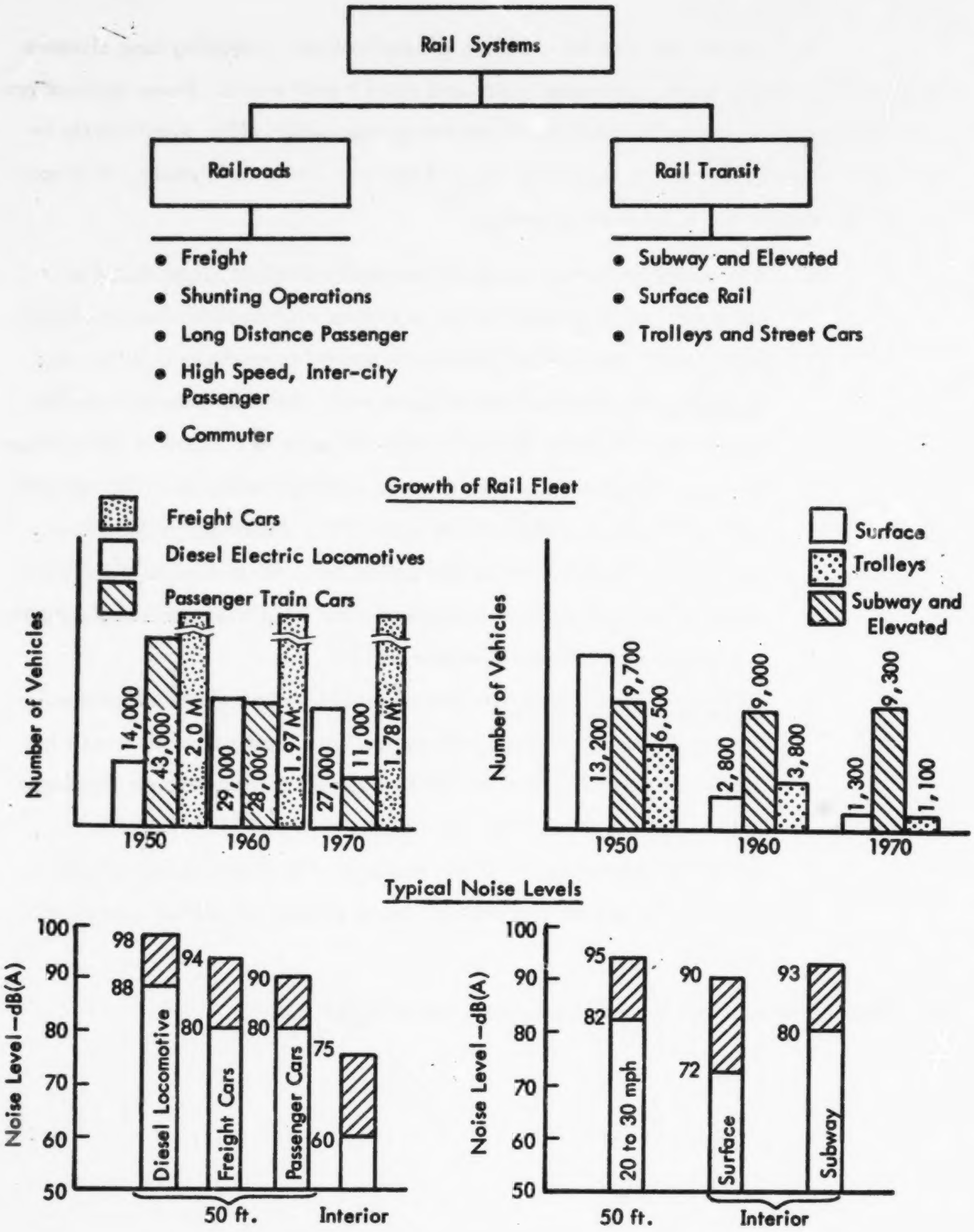


Figure 2.5-1. Characteristics of Rail Systems

2.5.2 Source Noise Characteristics

Railroads

Noise in railroad systems can be separated into the contributions of two basic sources, the locomotives and the train vehicles which the locomotives haul.[1, 4-10]

- Locomotives – The total number of locomotives in service in the United States was slightly over 27 thousand at the beginning of 1971. Of these, 99 percent were diesel-electric locomotives, and the majority of the remainder were electric. Approximately one-half of the locomotives are used for main line haulage and are generally powered by engines of 1800 horsepower and greater. Lower powered locomotives are used for short-haul trains and as switchers in the railroad yards.

  The major source of noise in this group is the diesel-electric locomotive. Typical noise levels under various load conditions and speeds are shown in Figure 2.5-2. The propulsion system includes a diesel engine, usually 8- to 16-cylinder, that drives an electrical generator. This generator in turn provides power to traction motors on each axle of the locomotive. The diesel engine is water-cooled and thus requires a radiator and associated cooling fans, situated in the roof of the locomotive. Dynamic braking is used to slow the locomotive and train at higher speeds, and is accomplished by disconnecting the traction motors from the main generator, using them as generators. The high electrical currents that result are passed through heavy duty resistors which are cooled with the use of separate fans in the roof of the locomotive.

  The sources of noise in a moving diesel-electric locomotive are, in approximate order of contribution to the overall noise level:

  - diesel exhaust muffler
  - diesel engine and surrounding casing, including the air intake and turbocharger (if any)
  - cooling fans

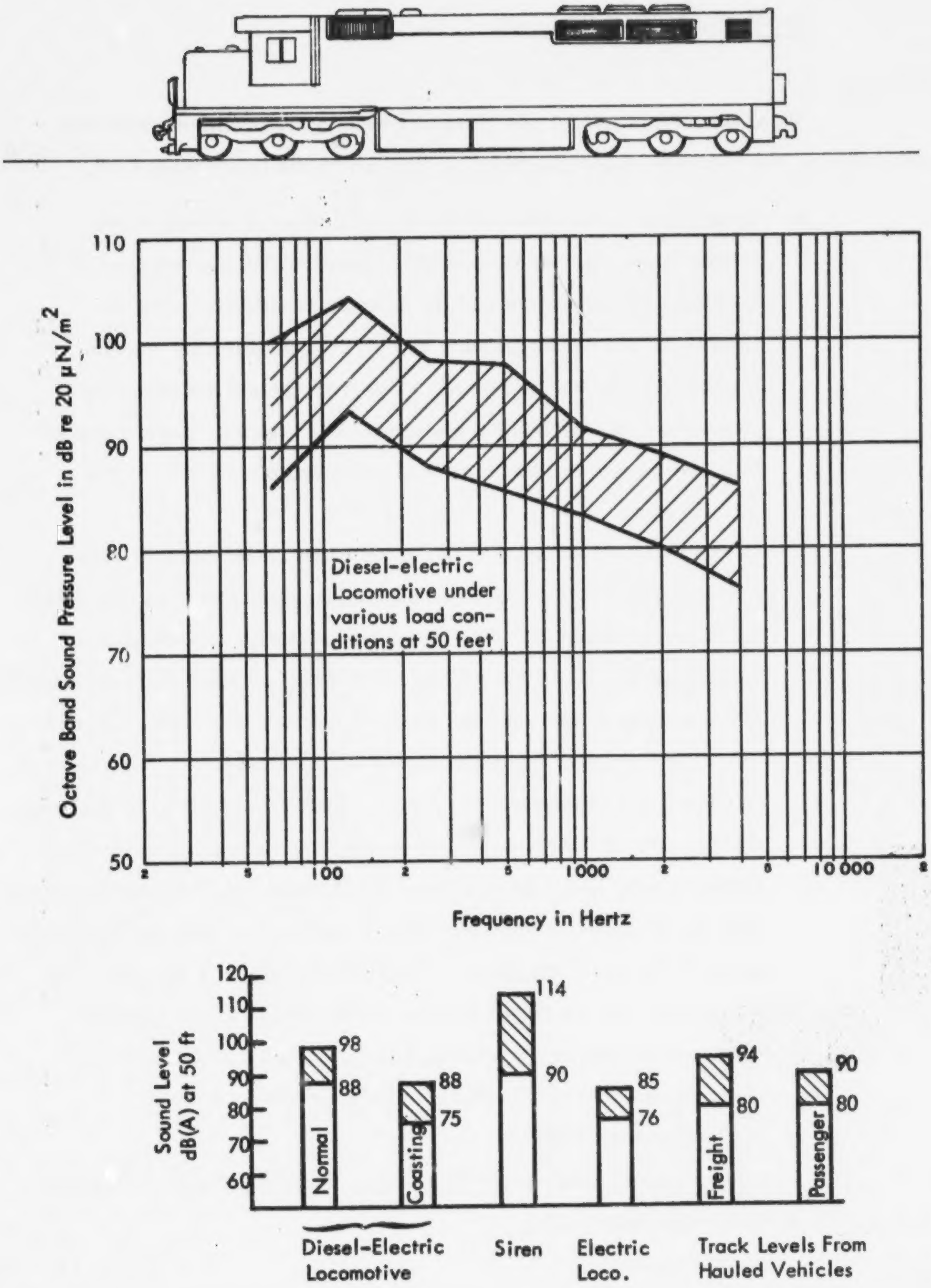


Figure 2.5-2. Wayside Noise Levels and Spectra of Railroad Equipment

- wheel/rail interaction
- electrical generator

An additional source of noise is the siren or horn, which produces noise levels 10 to 20 dB greater than that from the other sources. This is not a source that is operated continuously, however (30 times per hour on a typical run), and is a necessary operational safety feature causing it to be excluded from the above list.

The electric locomotive draws electrical power from a catenary. This electrical power is converted for application to the traction motors by means of transformer rectifiers and smoothing reactors. The braking is similar to that described for the diesel-electric locomotive, with the exception that blowers are used in place of fans. The major noise sources from the electric locomotive are as follows:

- cooling blowers
- wheel/rail interaction
- electric traction motors

The electric locomotive produces most noise when braking from high speeds, the increase in noise over that of normal operation being due to the operation of the dynamic brake resistor cooling blowers. Braking from high speeds is normally an operation that is confined to rural areas, so the noise impact is not severe. If this operation is ignored, the electric locomotive is considerably quieter than its diesel-electric counterpart, as shown in Figure 2.5-2.

- Train Vehicles – The other main noise source associated with railroad trains is that of the vehicles being hauled. Typical wayside noise levels for freight and passenger cars are shown in Figure 2.5-2. Freight and passenger cars have no propulsion system of their own, so that the exterior noise produced is due mainly to the interaction between the wheels and the rails. The magnitude of the noise depends heavily on the condition of the wheels and track, whether or not the track is welded, and on the type of vehicle suspension. Modern passenger vehicles with auxiliary hydraulic suspension systems in addition to the normal springs can be 5 to 10 dB quieter than the older type with springs alone. However, most freight cars have the simple spring suspension. Additional noise can be produced by empty boxcars with loose chains and vibrating sections.

The noise inside passenger vehicles is also partly due to the wheel/rail interaction. Typical interior noise levels are shown in Figure 2.5-3. This noise is produced in two ways. First, there is broadband noise due to the inherent roughness both in the wheels and the rails. At high speeds, variations on the order of a few thousandths of an inch are sufficient to produce high noise levels. Secondly, there is the impact of the wheels as they pass over the rail joints, producing the familiar "clickety-clack." There are two paths by which this track noise reaches the passenger. First, there is the direct mechanical path from the wheels through the suspension and hence to the car body. The resulting vibration of the body radiates sound to the interior of the car. Secondly, there is the airborne path from the track through the car body and windows. This latter path becomes more important when the train is passing through cuttings and tunnels. The introduction of the welded track eliminates impact noise, leaving the broadband track noise. At present, only about 10 percent of the nation's railroad tracks are of the welded type, but the amount of welded track is being increased at the rate of 3000 miles per year as the older sectional type requires replacement. In addition to the track noise, interior passenger car noise is created by the air conditioning system. This is the typical broadband "rushing" noise emanating from the exit and return grilles, usually in the roof of the car.

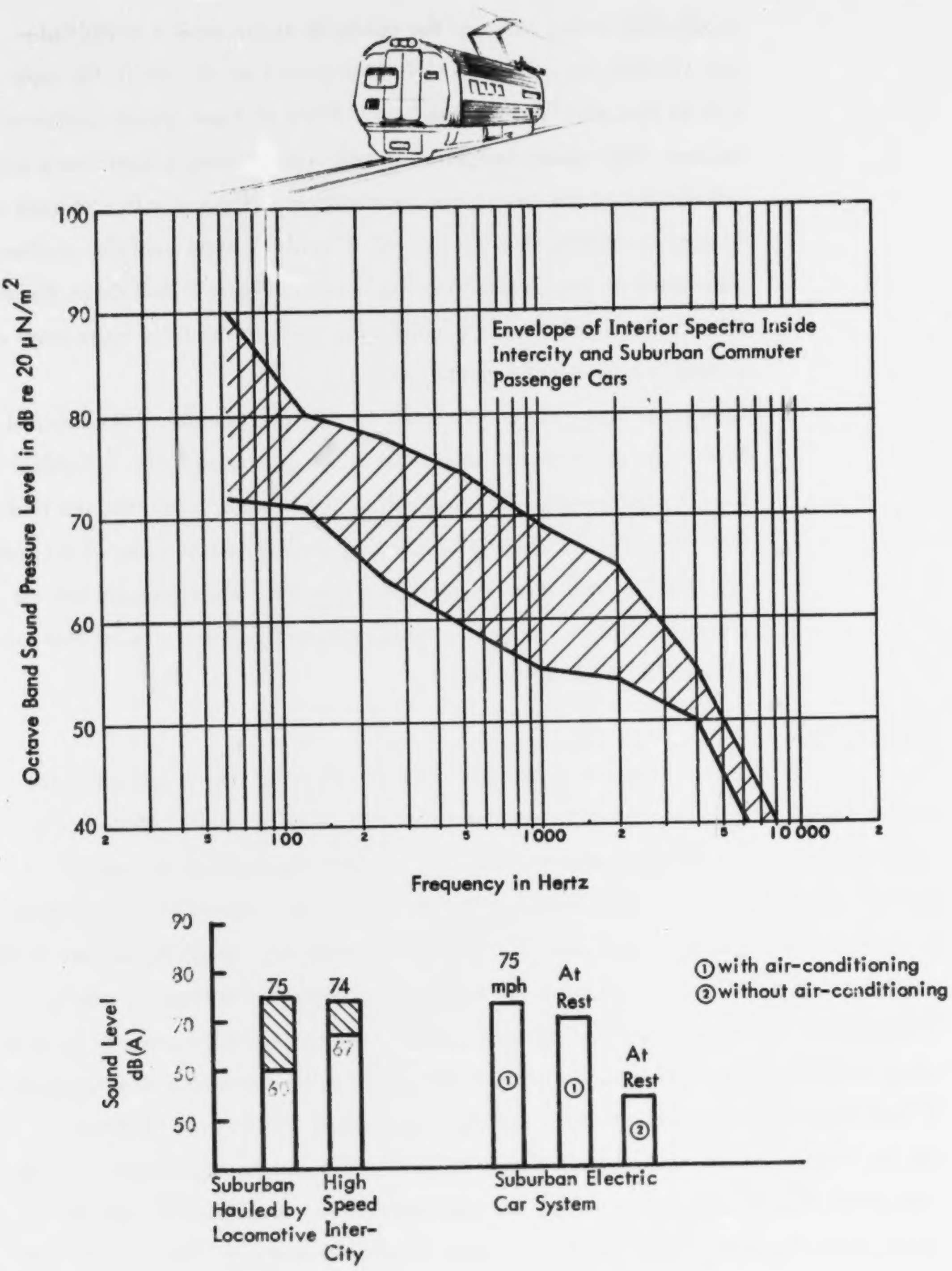


Figure 2.5-3. Train Vehicle Interior Noise Levels and Spectra

In suburban areas, many of the commuter trains consist of multiple-unit electric car systems in which the motors on all cars in the train may be operated from the lead car. Many of these systems consist of modern, high-speed equipment in which noise level criteria were considered during the design and construction. If the wheels and track are in good condition, the interior noise levels of these vehicles is often dependent on the air conditioning system. Figure 2.5-3 shows the contribution of track and air conditioning noise to the total noise level of a modern high-speed suburban rail car.

One other major source of noise from railroad operations is produced in retarder yards where freight trains are assembled. The individual freight cars are allowed to roll along the selected track and are braked automatically or manually before they strike the remainder of the train. The braking mechanism consists of a steel rail that is pressed against the wheel flange, producing a high-pitched sound at a level that can exceed 120 dB(A) at 50 feet.

Rapid Transit Systems

At the beginning of 1971, there were 15 rail rapid transit systems in the United States. Of these, 7 were subway and elevated, 4 were solely surface and 4 provided inter-urban surface transportation. All of these rapid transit systems use electric multiple-unit rail cars, designed for fast loading and unloading of passengers. A minimum amount of seating is provided since the average trip length is between 3 and 5 miles. Consequently, in rush hours the number of passengers standing can easily exceed those seated by a factor of three or greater. Ease of entrance and exit requires many doors which are wide enough for these operations to be conducted simultaneously. In addition, to obtain good general visibility, large-sized windows are utilized. Efficient operation of a transit train also requires that the cars be lightweight so as to reduce the overall load to be hauled, the time required for acceleration, and the motor size and power. All these factors result in vehicles that are inferior to railroad passenger cars as far as acoustic insulation is concerned. Suspension systems universally contain steel springs, additional cushioning being provided by either rubber pads or air cushioning systems.

There presently exists a wide mix of vehicles in operation in terms of age and condition. The older type of vehicles that still operate on all existing systems in general have a poorer suspension system than those more recently introduced. There is also a definite requirement to use air-conditioned vehicles that allow all windows to be permanently sealed. These improvements have enabled the modern vehicle to be a significant improvement over the older type as far as noise and comfort are concerned.

The electrical power for rapid transit trains is collected by means of a shoe from a third rail and is applied to traction motors, one for each axle of the vehicle. The motors drive the axles through a gearing system. Most systems use compressed air braking systems, the exception being the Chicago Transit Authority which uses all electric braking.

In addition to the electrical power required for propulsion, power is also required for door operation, lights, fans, heaters and a host of other utilities. Since the power required for those utilities differs from the type picked up externally, it is usual to include batteries together with a motor alternator to provide ac power and a motor generator set to charge the batteries. The motor alternator is used continuously, whereas the motor generator and air compressor work only when required. Air conditioning is provided by means of fans and cooling systems. The lack of space under the vehicle dictates that this system be small. This means a high pressure system is required to obtain the necessary air flow, which in turn results in high interior noise levels as the air passes through the vents. All the electrical motor systems are situated underneath the vehicle and require a passage of forced air over them both for cooling and dirt removal. Air fans or blowers are therefore required to provide the necessary air flow, and these are often operated continuously.

The major noise sources associated with rapid transit systems are, in order of their contribution to the overall level, as follows:

- wheel/rail interaction
- propulsion system
- auxiliary equipment

Typical ranges of wayside noise levels from rapid transit vehicles, together with the contribution from the various individual noise sources, are shown in Figure 2.5-4.[8, 11-14]

The main source of noise is the interaction between the wheels and rails. This source is more serious in rapid transit systems than in rail systems because the tracks are subject to a much higher amount of wear. Unevenness in the track is produced by flat spots in the vehicle wheels and by heavy braking as the train enters the station. Once this unevenness is initiated, the track continues to deteriorate with further passage of trains.

Another wheel/rail interaction occurs at small radius curves in the track, where the difference in speeds between wheels on the same axle and the rubbing action of the wheel flange on the rail can produce a severe squeal. This source may increase the normal track noise level by 10 dB or greater, the increase occurring mainly at discrete frequencies.[15-17]

The noise from a rapid transit system is complicated, however, because of the effect of elements not totally connected with the vehicles. First, there is the pronounced effect of tunnels in subway systems. The surfaces of tunnels are hard and acoustically very reflective. Hence, the noise from the sources outlined above is now effectively being radiated into a reverberant enclosure. It is thus possible to obtain much higher noise levels (as much as 10 dB greater) than those out of tunnels. This effect is also found in below-ground subway stations which tend to be fairly reverberant. Noise levels inside rapid transit rail vehicles above and below ground are shown in Figure 2.5-5.[18-23]

Secondly, there is the effect of aerial structures where the track is supported by concrete and/or steel frameworks above the surrounding city. The track on these structures is less rigid than it would be at grade level on a solid foundation. Therefore, noise levels 2 to 5 dB higher can be expected due to increased vibration not only of the track but sometimes of the structure itself. In some aerial structures, there is a

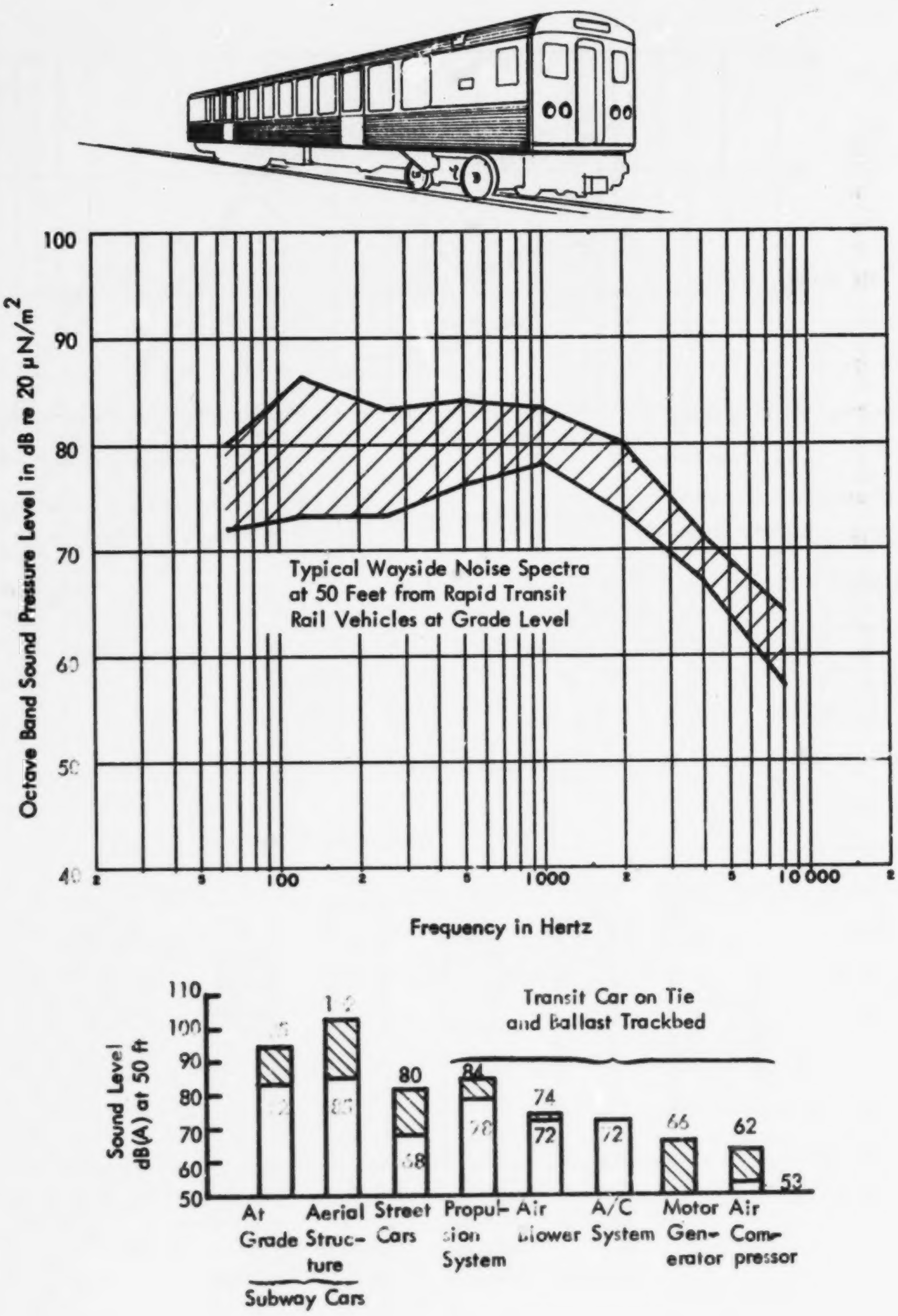


Figure 2.5-4. Wayside Noise Levels and Spectra for Rapid Transit Vehicles

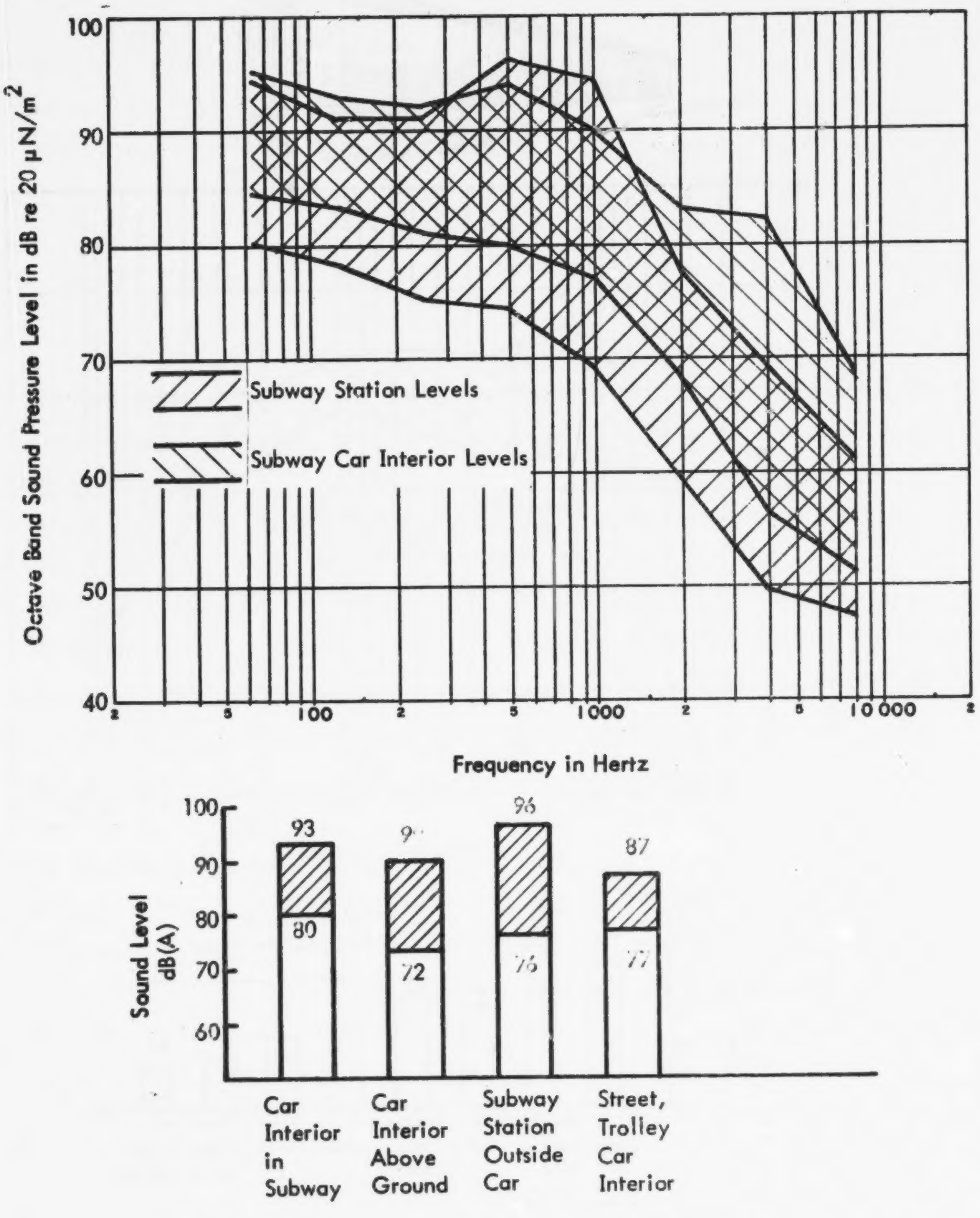


Figure 2.5-5. Subway Noise Levels and Spectra

direct airborne path from the underside of the train to the ground below. In these cases, extremely high noise levels can be experienced.

Finally, there is the effect of different types of track systems. Although reports vary on this subject, it appears that both the type of rail fastener used and the type of trackbed are significant as far as wayside and interior noise are concerned. For example, the highly reflective concrete trackbed produces higher exterior and interior vehicle noise levels than does the tie and ballast which is less reflective. Similarly, variations of up to 5 dB can be obtained by the use of different rail fasteners.[12,24]

Street and trolley cars still operate in Boston, San Francisco and Philadelphia and other cities, in some cases in a dual operation with subway systems. External noise levels vary in the case of streetcars between the old and the new type of PCC cars, the range being approximately 68 to 80 dB(A) [25] at 50 feet under varying operating conditions, as shown in Figure 2.5-4. Trolley cars are significantly quieter in the absence of the wheel/rail noise, producing external levels in the order of 68 dB(A). Internal noise levels are similar in trolley cars and in the newer PCC type of street cars, 77 to 80 dB(A), whereas in the few remaining old street cars the levels are approximately 5 dB greater.

2.5.3 Environmental Noise Characteristics

The noise levels experienced by people who live in communities adjacent to these systems depend upon the distance from the tracks as depicted in Figure 2.5-6 for various types of trains. In this figure, the majority of train types are included in a single band of estimated noise levels varying with distance from the train. Rapid transit trains tend to be in the lower half of this band, whereas locomotive-hauled trains (diesel-electric) are in the upper half. The length of trains varies from as little as 150 feet in transit systems to over 3000 feet for freight trains. Consequently, the duration of the noise for a single passby varies considerably from a few seconds up to one minute and perhaps longer.

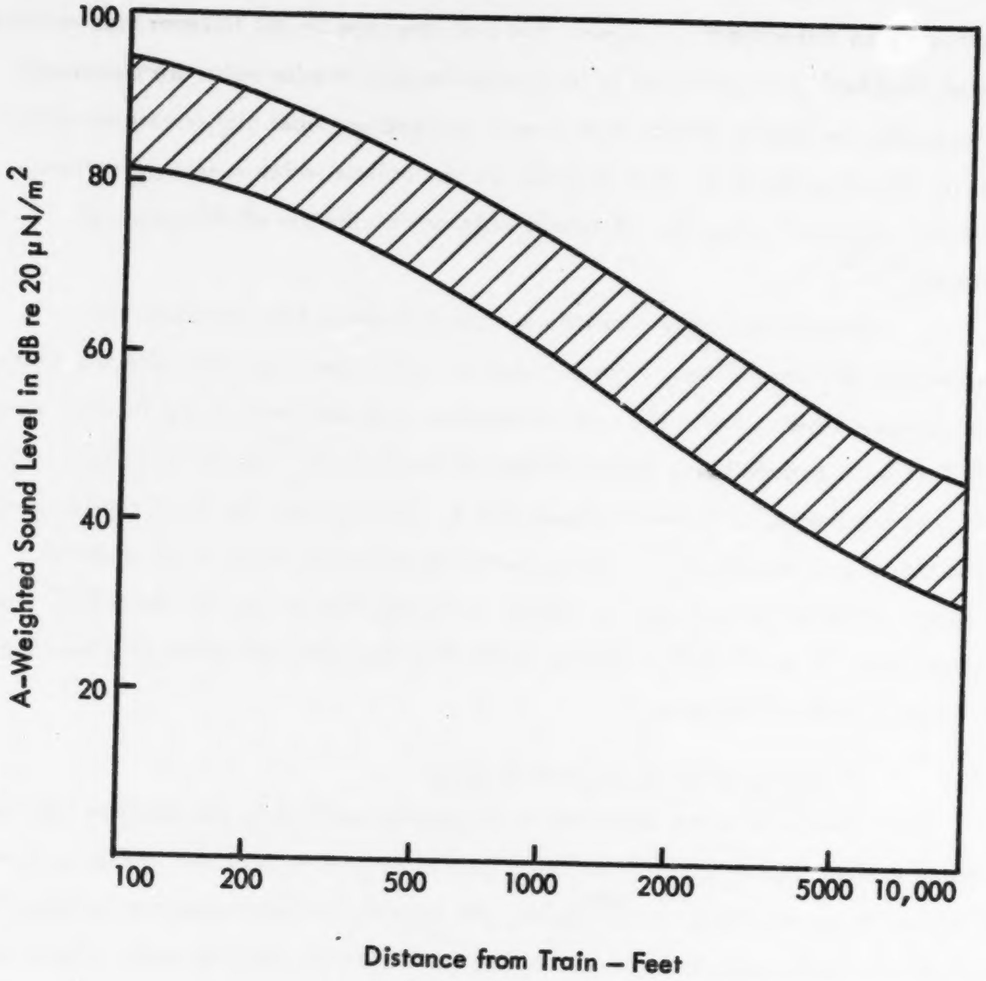


Figure 2.5-6. Noise Level as a Function of Distance from Train for Railroad and Rapid Transit

The noise levels experienced by people on-board the train or by persons waiting at the station for the train to arrive are in the range 60 to 75 dB(A) on long distance and intercity passenger trains, and 72 to 93 dB(A) on rapid transit systems. Noise levels in subway stations are higher on some systems, lying within the range 76 to 96 dB(A). The range of levels in transit systems encompasses trains both above and below ground under many varied conditions of operation.

Over 80 percent of the passengers using rail transit systems are carried on the subway and elevated lines. The number of passengers in 1970 averaged 4.3 million per day, the average trip length being 3 to 4 miles and the trip duration 0.2 hours. On railroad systems – including commuters – 780 thousand passengers were carried per day over an average trip length of 38 miles. The trip duration varies widely from 0.5 hours for commuter trains to several hours for intercity trains.

2.5.4 Industry Efforts in Noise Reduction

Railroads

The incorporation of noise-limiting requirements in the specifications for new rail vehicles has only recently caused industry to initiate noise abatement programs. Therefore, the majority of vehicles in operation today are not affected by these programs. The only requirements that manufacturers must meet in the specifications for locomotives concern the noise levels existing in the driver's cab. As far as wayside noise from railroad equipment is concerned, a small number of programs have been started and are at present in progress. These mainly concern the noise from diesel-electric locomotives, but detailed information as to the possible outcome of the program is not available at this time.

Diesel-electric locomotives have had little noise control applications other than to the interior of the cab. The exhaust system has no muffler, and the spark arrestor provides little attenuation. Since the exhaust is probably the major source of noise, it is possible that mufflers could be designed that would reduce the overall sound level. In addition, more substantial or modified casing around the diesel engine, together with acoustical absorbent material, may well be effective in reducing the noise from this source.

More attention has been paid to the noise produced by the passenger vehicles, both exterior and interior. The luxury-type railroad cars as well as the more modern commuter cars hauled by locomotives are equipped with rubber isolation pads and shock absorbers, in addition to the spring suspension systems common in the older stock. The reduction in wayside noise level is on the order of 10 dB or greater. As far as freight cars are concerned, improvements in functional performance over the years has had the effect of reducing the noise level as a by-product. There are, however, no programs in existence for the control of noise from freight cars.

The modern high-speed, intercity trains such as the Metroliner and the TurboTrain that travel at speeds around 100 mph have been designed to achieve interior levels in the region of 70 to 74 dB(A)[7] with air-conditioning equipment running. These trains have extensive carpeting, improved door seals, smaller windows (Metroliner) and acoustic insulation in the ceiling and wall structures. Wayside noise from the TurboTrain propulsion unit at operational power with the train stationary is 82 dB(A) at 50 feet.[26] In addition, the modern suspension system incorporated in the TurboTrain should result in lower interior noise levels than in the conventional passenger train.

Rapid Transit

The development of specifications for rapid transit vehicles is complicated by the division of responsibilities between the cognizant transit authority and the manufacturer. For example, a typical present-day specification concerns noise levels produced by propulsion units and auxiliary equipment with the vehicle stationary. It does not include the noise produced by the wheel/rail interaction which in most cases is the major contribution to the overall noise level. Nor does it take into account the effect of tunnels upon the interior noise levels in the vehicles. These factors are the responsibility of the Rapid Transit Authorities. Consequently, vehicles built to the specifications but operated on tracks that are not maintained in a good condition may therefore generate interior and exterior noise levels well in excess of those stated in the specifications. As a result, both the manufacturer and the customer (in this case the Rapid Transit Authority) are required to pursue separate programs to reduce the noise levels.

Much of the work that has been conducted by transit authorities has been on systems outside the United States. The result is that the transit systems in this country tend to be amongst the noisiest in the world, as shown in Figure 2.5-7.

The quietest systems in the world are in Berlin, Hamburg and Toronto. It is true, of course, that European countries in particular have placed and still do place more reliance on rail transportation. It is therefore natural that research and development would be of greater importance in these countries than in the United States, where rail passenger travel is on the decline.

However, investigations have not been neglected in this country. The Chicago Transit Authority (CTA) has conducted many experiments in an attempt to achieve some reduction in noise levels. More recently, New York, San Francisco and Washington, D.C. also have been particularly concerned with this problem, and do plan improved systems for the future.

A number of noise abatement programs have been conducted in the past, both by the equipment manufacturers and by the transit authorities. It was shown in Section 2.5.2 that there is a wide range of noise levels associated with transit systems, and that this exists because of the equipment used, the type of surroundings, and the degree of track and vehicle maintenance. The programs conducted by the transit authorities have been directed naturally enough toward the noise sources most important for their individual systems. The conclusions that will be drawn will therefore reflect what could be done now, using current technology, to reduce noise levels in rapid transit systems. It is difficult, however, to state overall quantitative conclusions as to the results of these programs because of the differences existing between systems. The following review of noise abatement programs will treat each major source of noise separately, as far as this is possible.[8, 12-16, 20, 27-29]

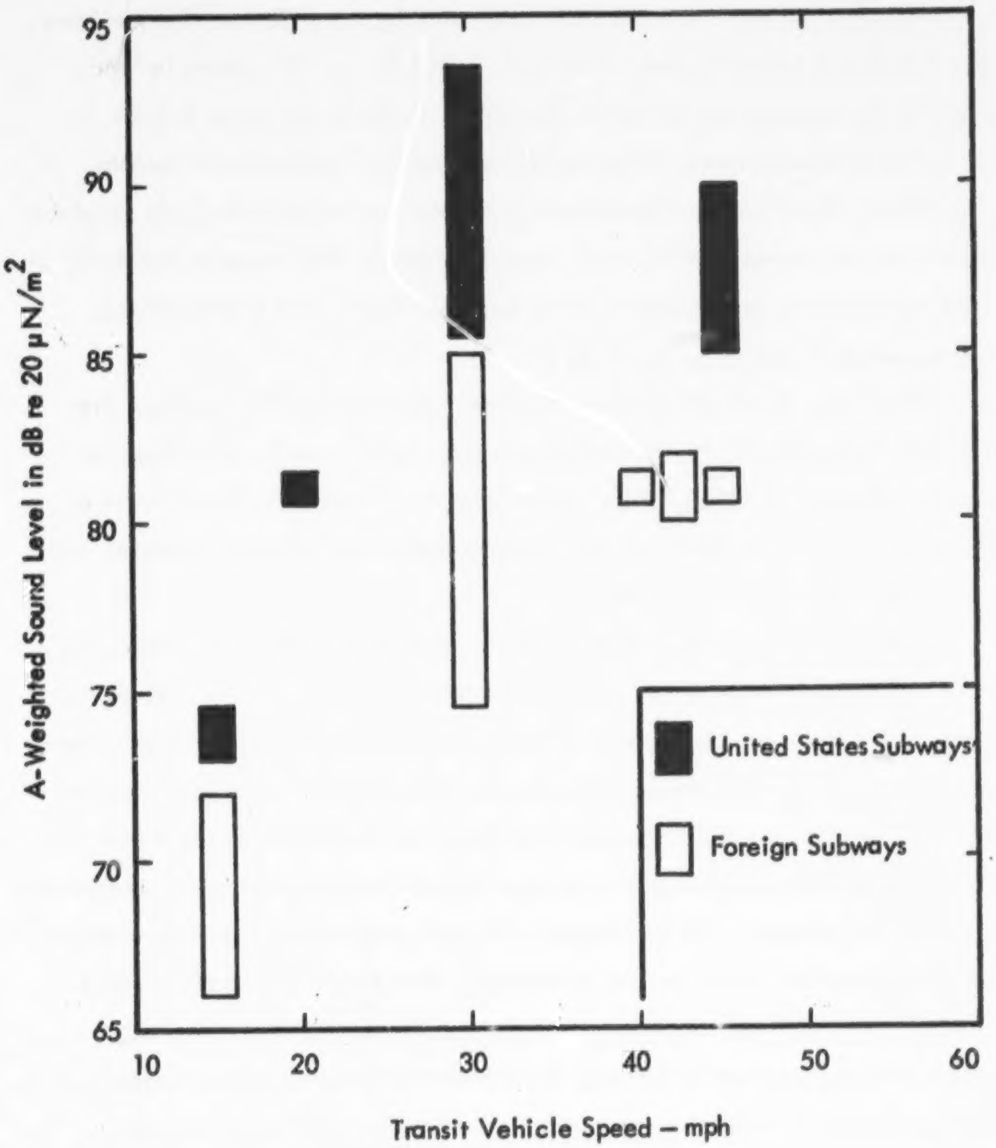


Figure 2.5-7. Comparison of Interior Noise Levels in Subway Transit Vehicles

- Wheel/Rail Interaction – The noise produced by the impact of the wheels on the joints of sectional rail is the dominant noise problem for almost all rail systems. The most successful approach to reducing this noise has been the use of continuous welded rail. Reductions on the order of 5 dB or greater can be obtained by this method. More systems are now incorporating this type of rail during rail replacement. The unevenness in the track in the form of corrugations that are the major source of noise in rapid transit systems can be removed by grinding. However, the track of some systems appears to be more susceptible to corrugations than others due to the differences in rail used and the variability in vehicle wheels and suspension.

  In order to reduce the vibration of the wheels and car body when the vehicle is operating on rough track, the possibility of resilient wheels has been studied. The results have not been conclusive due partly to the varying condition of the track in the different systems on which resilient wheels have been tried. Of the three systems in the world – Berlin, Hamburg and Toronto – that are considered to be the quietest, one (Hamburg) incorporates resilient wheels, the others use the conventional solid wheels. It has been confirmed, however, that the use of resilient wheels does result in a reduction of low frequency ground vibration. Other wheel treatments include the use of vibration damping material, sometimes constrained, applied to the truck wheels. Measurements of track noise from vehicles negotiating curves of various radii have shown noise level reductions of the wheel squeal ranging from 5 to greater than 15 dB. The higher values of noise reduction are usually determined by the noise levels in a narrow frequency band covering the main frequency of squeal. On a straight track, the reduction in wayside levels at 50 feet are on the order of 2 dB. In this case, wheel squeal is not evident and the small reduction in noise levels is obtained over a wide frequency range. At curves of small radius, attempts have been made to reduce the severe wheel squeal by lubricating the track with water, oil or graphite. Such systems have been fairly successful and have been installed at New York, Cleveland, Chicago and elsewhere.

An interesting program conducted by the Chicago Transit Authority involved the use of an experimental rubber rail head. This was quite a successful program in reducing track noise, but was accompanied by many practical complications and so was abandoned.

One method of reducing track noise that has been tried in a few cities (Paris, Montreal and Mexico City) is to use rubber tired vehicles on a concrete road bed. Reports on the effectiveness of these systems vary, but the general opinion is that the reduction in noise levels is not significant when compared with the noise of the more common steel wheels on steel rails if these are in good condition. It may be concluded, therefore, that in the absence of regular maintenance, rubber tires may result in lower noise levels, although it is reported that they require a great deal of maintenance effort. With welded track and regular maintenance, there is little evidence to indicate the advantage of rubber tires. Economically, rubber tire systems tend to be expensive, since a separate guidance system is required as well as a backup system of conventional steel wheels and track which is reverted to in the event of a tire failure. There is, however, one exception to the above generalization. The recently opened system in Mexico City is reported to be one of the quietest in the world, and is considered to be better than that of the other two rubber tire systems. One reason put forward for the lower noise levels is the use of a ballasted track bed as opposed to the concrete used in Paris and Montreal, but a final opinion will have to wait until a noise measurement program has been conducted.

There appears to be substantive noise data to support the use of ballast between the rails. The alternative that is often employed is a concrete slab which forms a good reflector of sound emanating from the underfloor equipment of the vehicle and the wheel/rail interaction. Ballast provides more absorption and has been shown to reduce interior noise levels by 3 to 4 dB, if structure-borne noise is adequately controlled. A similar reduction in exterior noise level may be expected if it is dominated by noise from the propulsion system or auxiliaries.

- Tunnels – The high reflectivity of tunnel surfaces coupled with the enclosed space results in higher noise levels for a given source sound power than it does in open space. The sound energy is confined to a small volume instead of being able to propagate away in all directions. A method of reducing the noise levels in tunnels is to apply acoustical material on the surfaces of the tunnel so as to reduce the reflectivity. This has been tried in Toronto with the result that the interior vehicle noise levels were reduced by approximately 10 dB. Although this is a solution for reducing noise, it is not necessarily feasible from an economic point of view. For example, there are over 100 million square feet of tunnel surface area in the New York subway system which is estimated would cost over $150 million to coat with an acoustic absorbent material. However, the cost is much less for underground subway stations, which are extremely reverberant, and the use of absorbent material can result in noise level reductions in the order of 10 dB or more.
- Vehicle Body – Noise reaches the vehicle interior by the transmission of external airborne noise through the body work and by the transmission of structure-borne vibration to the body work and its subsequent radiation. An integrated approach is thus required if interior noise

levels are to be reduced. Above ground, with no nearby reflecting objects, most of the interior noise is radiated from the floor structure, which provides a noise reduction in the range 20 to 30 dB in existing vehicles. Eliminating and sealing holes and cracks in the floor and installing a layer of damping material has been shown on New York transit cars to reduce the interior levels in prototype cars by approximately 10 dB. The amount of reduction obviously is dependent on the original condition of the floor.

A recent trend that substantially reduces interior noise levels is the introduction of air conditioning systems in modern transit vehicles. The older systems in general rely on open windows for ventilation, resulting in interior noise levels as high as 95 dB(A) in some subway trains. Closing the windows can result in a reduction of 10 to 15 dB in interior noise levels, depending upon the situation.

- Propulsion and Auxiliary Systems – The propulsion system in a rapid transit car ranks second in the list of sources contributing to the overall noise level. This ranking, however, assumes that the wheels and track are in fair to rough condition. If ground-welded track and wheels are used, it is possible for the propulsion system noise to be of greatest significance. Under these conditions, it is possible to achieve lower wayside noise levels by using an acoustically treated electric propulsion system with skewed armature slots and a force ventilated cooling system. The reduction in noise level compared to existing propulsion units having little noise control treatment is shown in Figure 2.5-8.[13] This figure applies to vehicles traveling close to their maximum design speed. At lower speeds, the noise levels may be lower than those indicated. Again, it must be emphasized that the track should be welded and maintained in good condition for these noise reductions to apply.

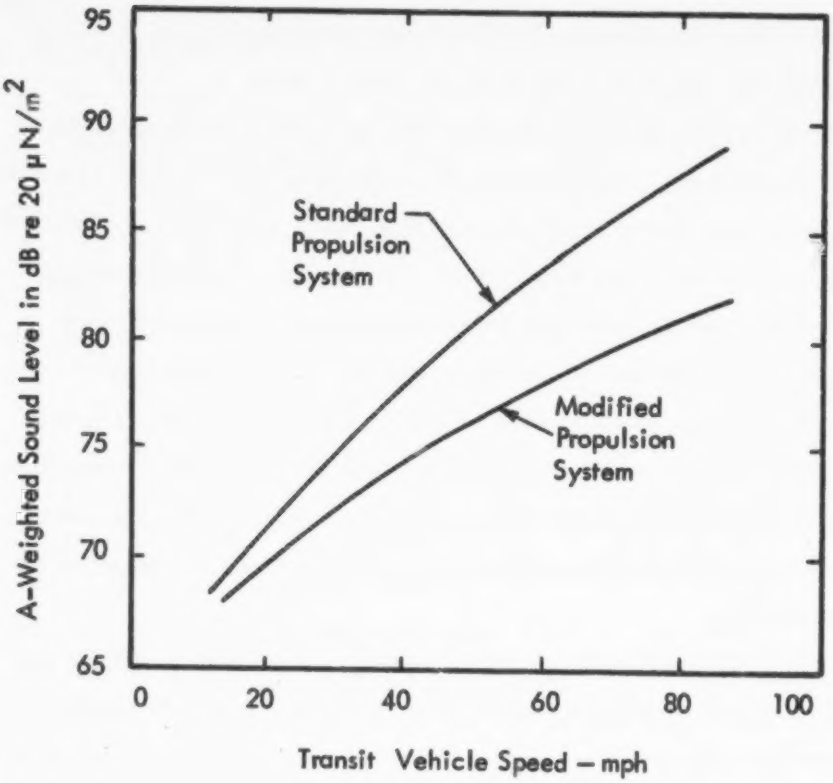


Figure 2.5-8. Noise Levels at 50 Feet from Steel Wheel Transit Vehicles on Tie and Ballast Trackbed for Maximum Vehicle Speed

Electric propulsion units drive the wheels through gears, the gear ratio varying from system to system, depending upon the power requirement. For a given vehicle speed, the resulting variation in motor rpm among the various systems gives rise to wayside levels that vary as much as 10 dB. High gear ratios are thus important as far as noise from the propulsion system is concerned. The application of improved or additional motor covers plus sound absorbing material, together with acoustic treatment of the motor cooling fan ducts, can result in a 6 dB reduction in noise level from motor units. The noise from the cooling fans contains pure tones associated with the blade passage frequency. Variable spacing of the fan blades makes these pure tones less distinct and produces a subjectively less annoying sound, even though the reduction in noise level is only 1 dB or so.

There are two main types of motor cooling systems – one that sucks air (self-ventilating), and one that blows air through the motor. The latter is preferable from a noise point of view, since noise control techniques can be applied in the blower ducts. It does have the disadvantage, however, that it remains in continual operation, whereas the self-ventilating type runs off the motor and hence is not operative in stations. Because of the lack of space under the vehicles, it is not usually possible to increase the size of the fans and have a lower flow velocity with an accompanying reduction in noise level. The same comments apply to the cooling systems for the auxiliary equipment on the vehicle.

- Barriers – Since the major noise sources in a rapid transit vehicle are situated underneath the vehicle body, one method of reducing the wayside noise level that has been tried has been the installation of a side barrier. The requirement for the design of the barrier is that it should prevent a line-of-sight to the underside of the vehicle from locations where the noise reduction is required. A simple barrier of this type, placed alongside the track and overlapping the vehicle floor by about 6 inches, can provide a 10 to 12 dB reduction in noise level at 50 feet.

An alternative to the installation of a barrier alongside the track, which could be extremely expensive, is to place skirts on the sides of the vehicles. However, there must be a clearance of a few inches at the bottom so as to clear the track; so the noise reduction is only about 6 dB in this case. A combination of both types of barrier could result in noise reductions in excess of the 10 to 12 dB for the wayside barrier alone.

Even greater noise reductions (in the order of 15 dB at ground level) can be obtained by placing the track in a cutting. The amount of the reduction depends upon the depth of the cutting and the angle of elevation of the sides.

2.5.5 Noise Reduction Potential

A summary of the effect that the application of current technology could have on the noise levels produced by the various sources is given in Table 2.5-1. The railroad and rapid transit authorities, together with the manufacturers of rail equipment, are becoming increasingly aware of the noise problems associated with rail systems and are planning a number of future programs for noise reduction. In most cases, however, the programs are not defined in terms of final goals, but more to determine what reductions can be achieved using current technology. The following programs are among those that are planned:

Railroads

- A study of the noise characteristics of diesel-electric locomotives with a view toward eventual noise reduction.
- The development of a new type of auxiliary generator of electrical power or suburban, locomotive-propelled, commuter trains.

Table 2.5-1

SUMMARY OF THE NOISE REDUCTION POTENTIAL BY APPLYING CURRENT TECHNOLOGY TO EXISTING TRANSIT VEHICLES

Existing Condition	Modified Condition	Estimated Noise Reduction dB	
		Car Interior	Car Exterior
Standard track, not regularly maintained	Welded track, ground	5-15	5-15
Concrete trackbed	Ballast trackbed	0-5	0
Bare concrete tunnel surfaces	Strips of absorbent material at wheel height	5-10	-
Bare concrete station surfaces	Limited absorbent material on wall surfaces and under platform overhang	-	5-10
Old type vehicles using open windows or vents for ventilation	New type cars with air-conditioning	10-15	-
Standard doors and body	Improved door seals, body gasket holes plugged, et cetera	0-5	-
Standard steel wheels	Steel wheels with constrained damping layer	5-15	5-15
Standard type vehicles	Installation of a 4 ft. barrier alongside track	-	10-15
	Installation of a skirt on side of vehicles	-	6
Standard, noisy propulsion unit	Modified unit with skewed armature slots, random blower fan blade spacing, acoustically treated fan ducts	0-5	5

Note: The values of noise reduction are estimated for the particular source alone, assuming no contributions from other sources. The values therefore cannot be added to obtain an overall noise reduction.

- Improved suspension system for the TurboTrain which, it is estimated, may reduce interior noise levels from 74 dB(A) to 60 to 65 dB(A).[30] Due to the noise from the air-conditioning system, the noise reduction obtained may be less than this. The final levels may be in the range of 65 to 70 dB(A), depending on the position in the car, unless the air-conditioning equipment noise is reduced.
- The replacement of old track by welded track. About 3 thousand miles of track per year are renewed in this manner.

Transit Systems

- The application of spray-on acoustic absorbent material on the ceilings and under the platform edges, together with noise barriers between tracks at a New York subway station. This is intended as a demonstration program that is estimated to provide 6 to 7 dB noise reduction. The total cost of this experiment will be about $75 thousand.
- The replacement of old transit cars with more modern types incorporating air-conditioning, door and window seals, rubber suspension mounts and vibration damping materials on the body. It is estimated that a 10 dB reduction in interior noise levels will result. This is a definite program in New York, Chicago and San Francisco, and is a trend that is being followed by most transit authorities.
- The replacement of old track with welded track in many transit systems.
- The New York City Transit Authority is replacing old track with a new type incorporating a rubber rail pad. Previous tests have shown that this provides a more comfortable ride and reduces interior noise levels.
- A study to determine whether improved sound insulation of transit cars can be achieved without increasing the mass of the car body. Along with this is a study to improve door seals.

- Design of an integrated heat transfer system for air-conditioning equipment that uses cooling coils or fans that are operated while the train is out of the station area.

2.6 Ships

2.6.1 Introduction

The United States merchant fleet consists of approximately 2000 active vessels of 1000 gross tons or greater.[1] Of these vessels, about 180 are combination passenger/cargo type, their average age being over 20 years. The number of ships capable of transporting passengers has been decreasing since 1950, and in this time only about seven new passenger/cargo ships have been completed by American shipyards. In 1971 the total number of passengers transported by sea from the United States to foreign countries was 1.7 million. Not all these people, however, traveled on U.S. ships.[2]

In recent years, the trend toward larger merchant ships constructed of lighter materials has resulted in an increasing number of excessive shipboard noise and vibration problems. Specifications for the construction of ships tend to be rather loosely written, without specific performance requirements for the levels of noise and vibration. This practice allows the delivery of ships without adequate noise control, and often makes it difficult to determine the responsibility for any such problems that arise.

2.6.2 Source Noise Characteristics

Of all the sources of noise in transportation systems, ships are probably the least important in terms of an environmental impact on the community in general, although noise problems may occur on board ship. There are three principal reasons why ship noise does not impact the community:

- The major sources of noise on a ship are the engine, gears, and propeller. This equipment is all below the water level and/or is enclosed by the structure of the ship, and most of the sound energy generated is radiated into the water.

- As far as airborne noise radiation is concerned, the sources of noise are the vibrating structure of the ship, the ventilation blowers, and the engine exhaust (funnel) where applicable. However, the hull vibrations are primarily at very low frequencies, and the noise from air moving devices is generally controlled sufficiently to make the noise levels on the deck acceptable for speech communication.
- The only time that a ship produces an appreciable wayside noise level is when it is under full power which occurs only when the vessel is out at sea. In ports, ships rarely exceed 5 knots, so wayside noise is negligible except for horn blasts which are generally well received by people living in port towns and cities.

The principal sources of shipboard noise are:[3,4,5]

- Propulsion System and Auxiliary Machinery – This includes gearboxes, turbogenerators, stabilizers, et cetera. The propulsion motors operate at a very low rotational speed compared to that of other transportation systems and consequently, the noise produced by the majority of the equipment is predominantly at the low frequencies. Gearboxes and turbines produce noise at the higher frequencies due to gear-tooth impact, and are audible in many of the cabins, particularly those located inboard in the vicinity of the engine rooms.
- Ventilation Systems – This equipment produces broadband noise typical of air conditioning and ventilating units, and is usually more obtrusive in tourist sections than in first class.
- Movement of People – This is mainly impact noise produced by people's footsteps on the deck above the observer. It is possible for such impacts to propagate considerable distances as structure-borne vibration.

- Plumbing Noise – This is due to the passage of water through pipes and faucets.
- Bulkhead Noise – The creaking of bulkheads with the movement of the ship, perhaps caused by wave impact. The noise is due to relative motion of the bulkhead panels and their supports.

In addition to these sources of noise, there are a number of sources of structural vibration that can be radiated as airborne noise from walls and floors,[5,6] including:

- Propeller – This is primarily a source of very low frequency vibration that can produce rattles in loose objects in the aft part of the ship.
- Propulsion System – As discussed above.
- Wave Impact – This is more a random than periodic occurrence and can be transmitted throughout the ship's structure.

The noise levels existing in a passenger ship (20 thousand to 25 thousand gross tonnage) at normal cruise speed are given in Figure 2.6-1.[3,6] These vessels are capable of carrying approximately 1000 passengers. There is a fairly wide spread of levels corresponding to first and tourist class accommodations in various areas of the ship. In general, the levels are higher on the lower decks than on the upper decks.

Little has been done toward changing the noise levels in cabins, except for installing ventilation systems which have high speed airflow. There is, in fact, a scarcity of data on the individual noise sources and the levels that they produce throughout a typical commercial ship. Some of the problems, such as impact, plumbing and bulkhead noise, could be reduced in magnitude by using similar techniques to those used in buildings. Although it is possible to reduce the noise from air conditioning systems using present technology, in many cases this steady state noise masks the intermittent rattling and creaking of the structure which might be otherwise disturbing. In addition, further reduction of the noise level might lead to a new requirement for better transmission loss between cabins to recover adequate privacy.

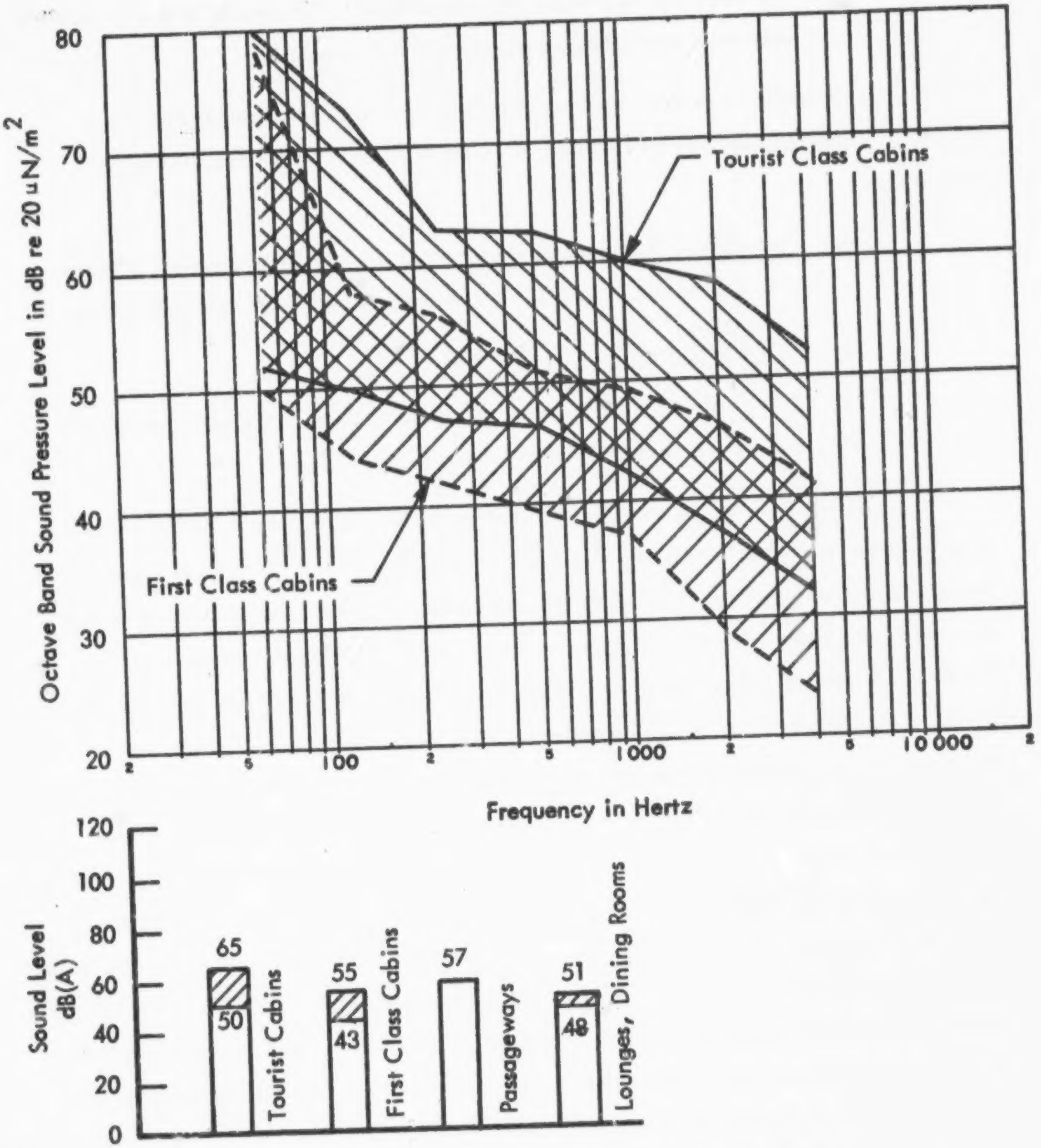


Figure 2.6-1. Noise Levels and Spectra on Ships

2.6.3 Environmental Noise Characteristics

As previously stated, the only environment which is significant in an analysis of shipboard noise is the area within the ship itself. These levels, as shown in Figure 2.6-1, are generally lower than 65 dB(A), and appear to have found general passenger acceptance over the years.

2.7 Recreation Vehicles

2.7.1 Introduction

Recreation vehicles, as defined herein, include pleasure boats, snowmobiles, all-terrain vehicles and motorcycles. There has been a remarkable growth in the number of these vehicles in the last 20 years. This growth is a reflection of the greater amount of leisure time and availability of these vehicles at attractive prices. Figure 2.7-1 summarizes the general characteristics of this category in terms of growth patterns and typical noise levels. The following paragraphs discuss pertinent aspects of the major vehicles in this category.[1-4]

- Pleasure Boats – The pleasure boating industry has enjoyed a relatively steady increase in sales over the past 20 years, from 2.8 million outboard motors in use in 1950, to around 7.2 million in use in 1970. There are currently over 8.8 million recreational boats in use in the United States. Of this number, 627 thousand are inboard motorboats and 5.2 are outboard motorboats. The boating industry estimates that over 44 million persons participated in recreational boating in 1970, and that $3.4 billion were spent on retail sales and services.
- Motorcycles – Motorcycles have experienced a remarkable increase in popularity over the last 10 years. Over 90 percent of the 2.6 million motorcycles in the United States today are used primarily for pleasure and are operated in many residential and recreational areas. The number in use is expected to increase to 9 million by 1985. Estimates for retail sales of new motorcycles in 1970 reached $440 million and used motorcycle sales reached $142 million. Parts and accessory sales amounted to $155 million for an aggregate of $737 million in sales. More than 8 thousand people were employed by motorcycle and parts manufacturers in 1970.

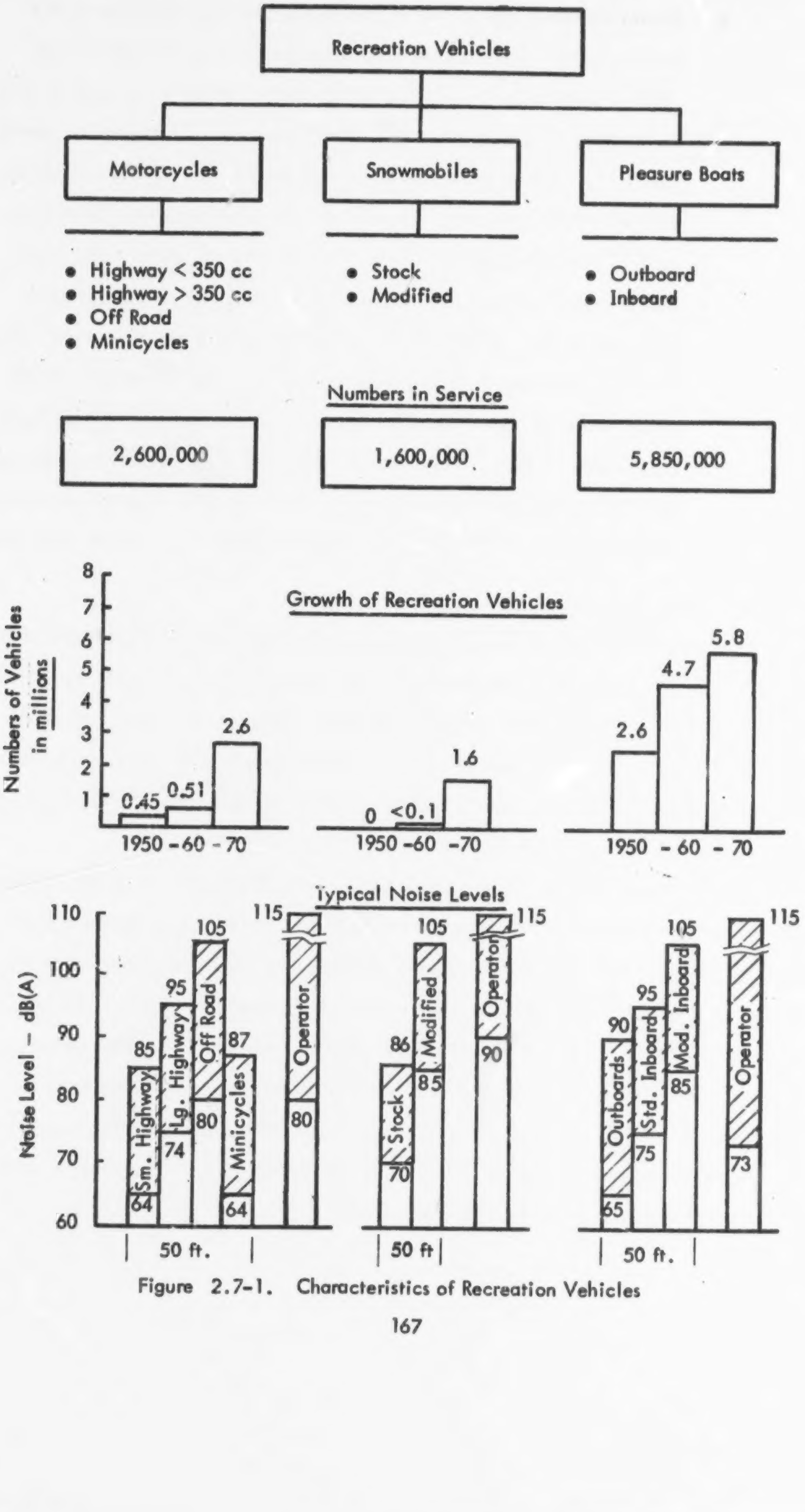


Figure 2.7-1. Characteristics of Recreation Vehicles

- Snowmobiles – This is one of the faster growing industries in the leisure field. Over 600 thousand snowmobiles were sold in the 1970-71 season in the United States and Canada, as compared with fewer than 10 thousand in the 1962-63 season. There are currently about 1.6 million snowmobiles in operation, the majority of which are recreation vehicles. Persons who live on farms own 28.5 percent of the snowmobiles. Many farmers and ranchers in the west and midwest rely on snowmobiles for feeding and rescuing storm-stranded cattle. In addition, foresters and utility servicemen often use these vehicles to make their rounds. Almost 80 percent of the people who own snowmobiles live in rural communities of 25 thousand population or less. The average enthusiastic snowmobile owner rides about 13 hours per week during the snow season. Approximate dollar volume for the 1970-71 sales season has been estimated at $600 million.

2.7.2 Source Noise Characteristics

The noise output of leisure vehicles, although dependent upon speed, is primarily a function of the way they are operated. Though many off-road motorcycles and some snowmobiles are capable of speeds of 80 to 100 mph, they are most often operated in the lower gears at medium to high engine output. Hence, except when cruising at constant speeds or coasting downhill, these vehicles are operated at high throttle settings and near their maximum noise output.

The major contributing source of noise from these vehicles is the exhaust. A high percentage of these vehicles operate solely off-the-road and hence are not licensed for highway use; therefore, many of the vehicles' exhaust systems are not silenced. As a result, these vehicles may create noise levels as high as 100 to 110 dB(A) at 50 feet.[5,6] Pending state legislation to regulate the noise produced by off-road machines has caused manufacturers to reduce the noise of vehicles in current production to 92 dB(A) at 50 feet.[7] The noise radiated from intakes and engine walls is also significant in these vehicles. Intakes are not generally silenced, and engines are either partially or totally unshielded.

The following discussions relate to the various types of vehicles that have been categorized as recreation vehicles.

Pleasure Boats

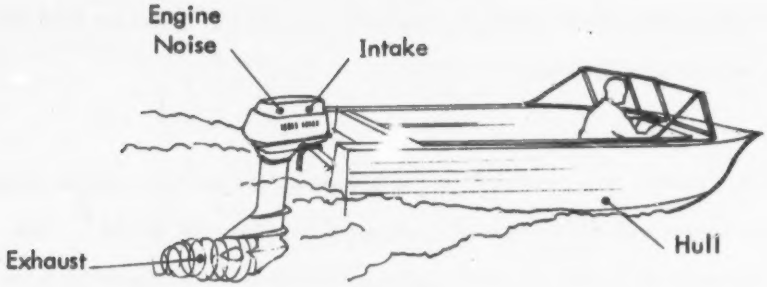
In a recent survey, the maximum noise levels measured for a large number of inboard and outboard powered pleasure boats ranged from 65 to 95 dB(A).[8] The lower limits of this range are created by small outboard powered craft (usually 6 to 10 horsepower).[9] In a different series of tests, levels exceeding 110 dB(A) at 50 feet were produced by inboard powered ski boats with unmuffled (dry stack) exhausts.[10,11] The typical range for noise levels produced by pleasure boats (by engine size and type) is illustrated in Figure 2.7-2.

Exhausts are generally the principal source of noise for pleasure boats. On the larger-engined ski boats, whose design incorporates a completely exposed engine, intake noise and engine mechanical noise also provide a significant contribution. As engine size is reduced, noise levels are typically lowered; however, in most cases, even though exhaust is exited under water, it is still the major noise source. In the medium and smaller outboard engine sizes, engine mechanical noise and intake (though acoustically shielded) provide noise output almost equal to the exhaust.

Motorcycles

The noise produced by motorcycles operating under cruise conditions is highly dependent on speed. Figure 2.7-3 depicts typical noise levels for various operating modes. Figure 2.7-4 illustrates a typical range of octave band frequency spectra for motorcycles under a variety of operating conditions. The relative contributions of the various subsources to the overall levels are also shown for a typical example.[12] The contribution of these subsources to the total noise levels are:[13,14,15]

- Exhaust — The exhaust controls the noise levels of motorcycles. In discussing exhaust system noise, a distinction must be made between 2-cycle (primarily imported) and 4-cycle machines. The noise spectra are of somewhat different character, with the 2-cycle


Engine Noise
Intake
Exhaust
Hull

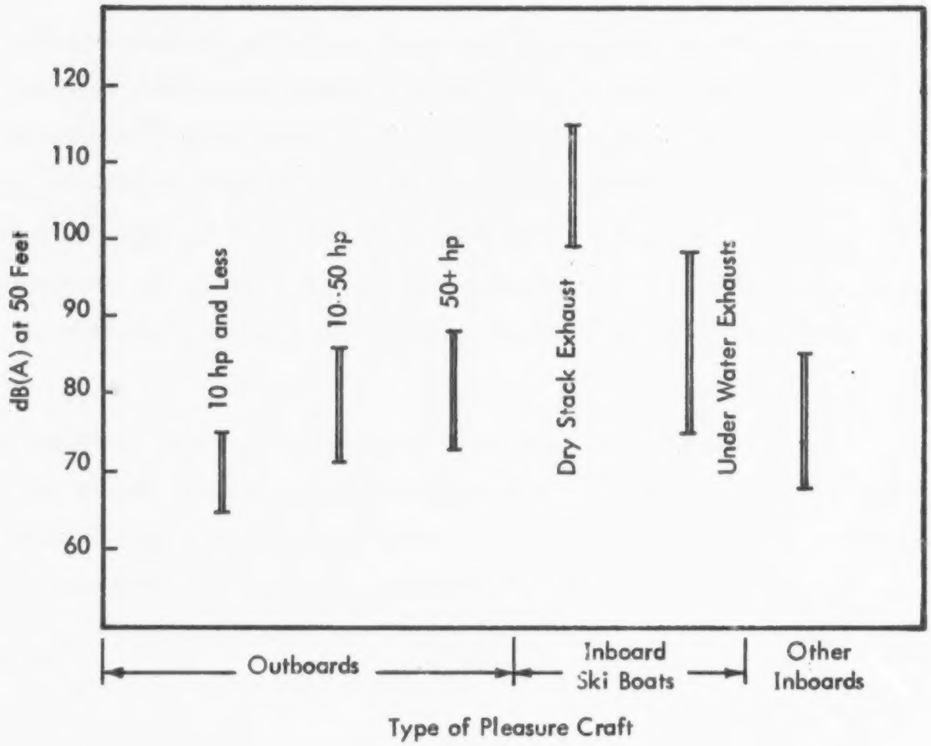


Figure 2.7-2. Typical Ranges of Noise Levels Produced by Various Pleasure Boat Types (dB(A) at 50 Feet)

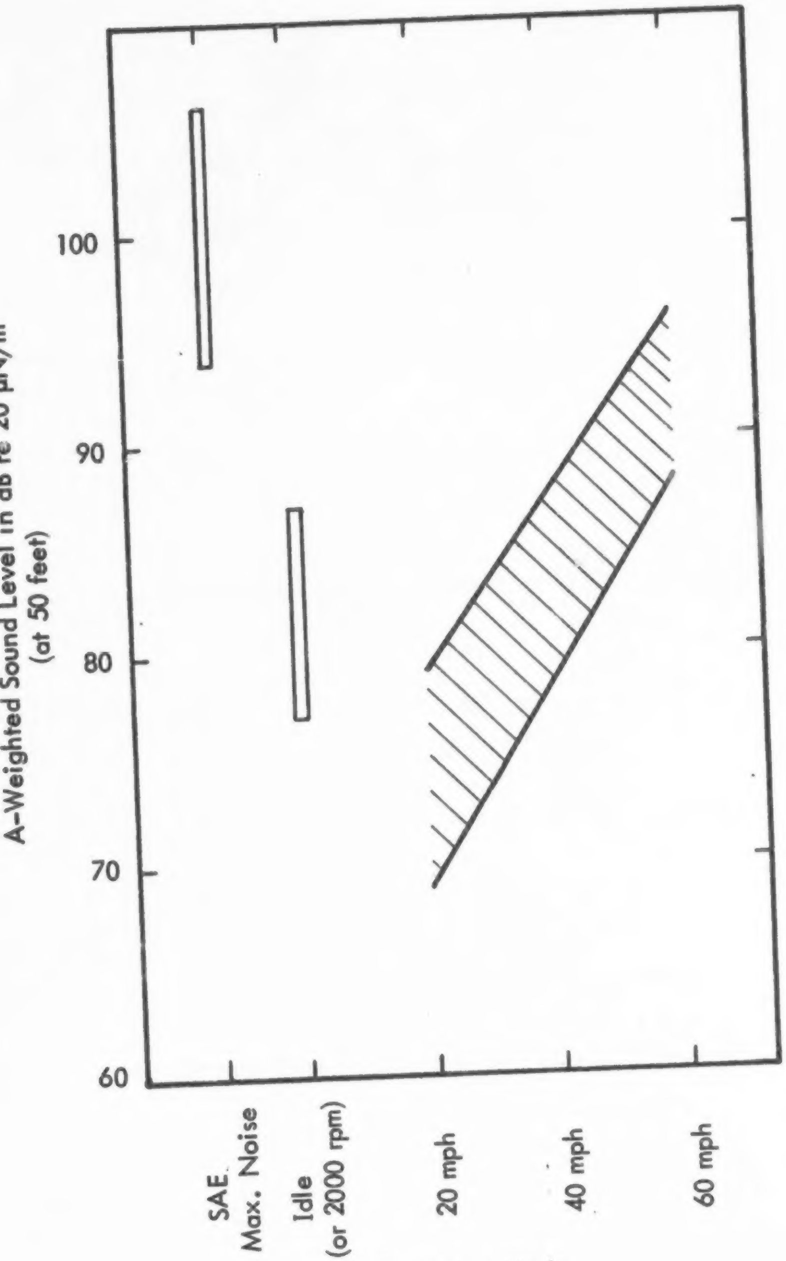


Figure 2.7-3. Motorcycle Noise Levels for Various Operating Modes

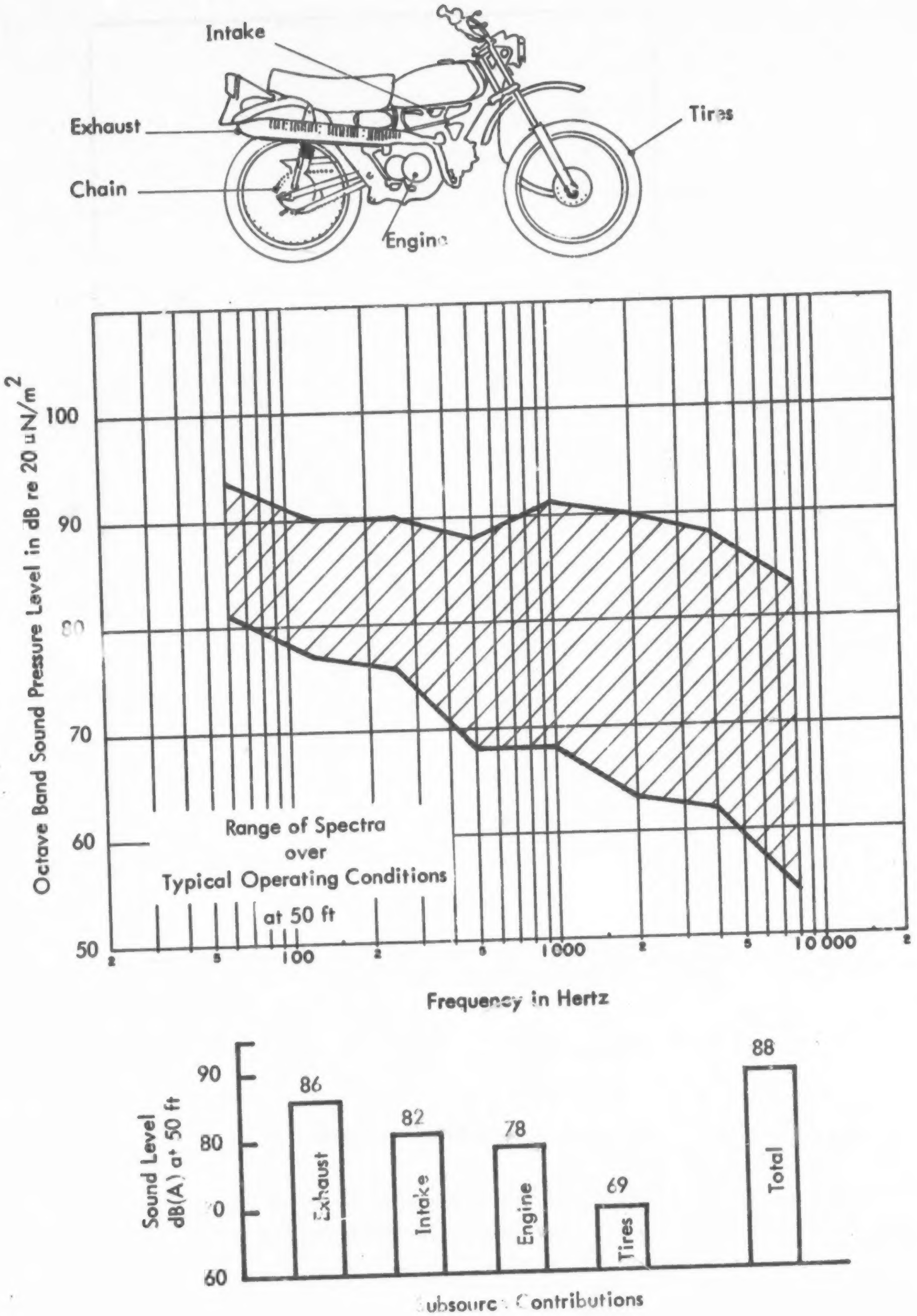


Figure 2.7-4. Motorcyle Noise

machines exhibiting more high frequency spectra energy content and the 4-cycle machines more low frequency content.

A major consideration in engine performance for 4-cycle motorcycle engines, over a specific rpm range, is exhaust pipe length. These machines must, by virtue of their design constraints, emphasize lightweight, compact construction. These requirements are not directly compatible with the basic principle of 4-cycle muffler tuning which equates the degree of silencing to gross muffler volume. Performance and economy are directly affected by silencing, as these machines rely on low backpressure to achieve competitive horsepower/weight ratios.

Two-stroke machines present less of an exhaust silencing problem. They are designed to incorporate an expansion chamber system (which is considered mandatory for 2-cycle performance), in which much of the acoustic energy is reflected back into the engine. This principle is used to advantage in achieving a supercharging effect on the combustion mixture as well as exhaust scavenging of the burned gases. A well-designed 2-cycle exhaust muffler system will actually increase power while at the same time reducing noise levels. This effect is found in the majority of 2-cycle engine applications with the exception of maximum output racing models.

- Intake – Noise radiated through the intake system is almost equal to the noise radiated through the exhaust system. Here again, performance and packaging considerations have minimized any silencing efforts in this area since both 2-cycle and 4-cycle designs rely on low intake restriction to achieve their power output requirements.

- Engine Mechanical Noise – Engine mechanical noise is the source of greatest concern in future reduction of overall levels. On current machines, engine noise is approximately the same order of magnitude as intake noise. The concept of acoustic engine enclosures and shielding has been considered almost totally impractical for lightweight air cooled motorcycles.

- Drive Chain and Tire Noise – Noise levels from these sources appear to be low enough to be considered of secondary importance. However, refinements to drive chain design may be warranted when contributions from other sources are reduced by at least 10 dB.

Snowmobiles

The noise produced by snowmobiles is highly dependent upon their age. Current production models produce noise levels in the range of 77 to 86 dB(A) under maximum noise conditions measured at 50 feet and 105 to 111 dB(A) at the operator position.[9,16] The noise levels from poorly muffled machines generally range from 90 to 95 dB(A) at 50 feet with racing machines causing levels as high as 105 to 110 dB(A).[5,17] The operator, on a number of machines surveyed, experienced levels in the range of 108 dB(A) under normal cruise conditions. Figure 2.7-5 shows typical octave band spectra for snowmobiles for a variety of operating modes, and presents a bar chart summary of those components which contribute to the overall noise levels.[5,14,18] The major contributors are:[19]

- Exhaust – A dominant source of snowmobile noise is the engine exhaust. Design constraints which minimize space and emphasize lightweight construction, and customer demands for maximum power have restricted the usage of adequate silencing devices.

- Engine Mechanical Noise – Another major factor in overall noise output of snowmobiles is engine mechanical noise. The lightweight, 2-cycle, high power design of the snowmobile power plants restricts

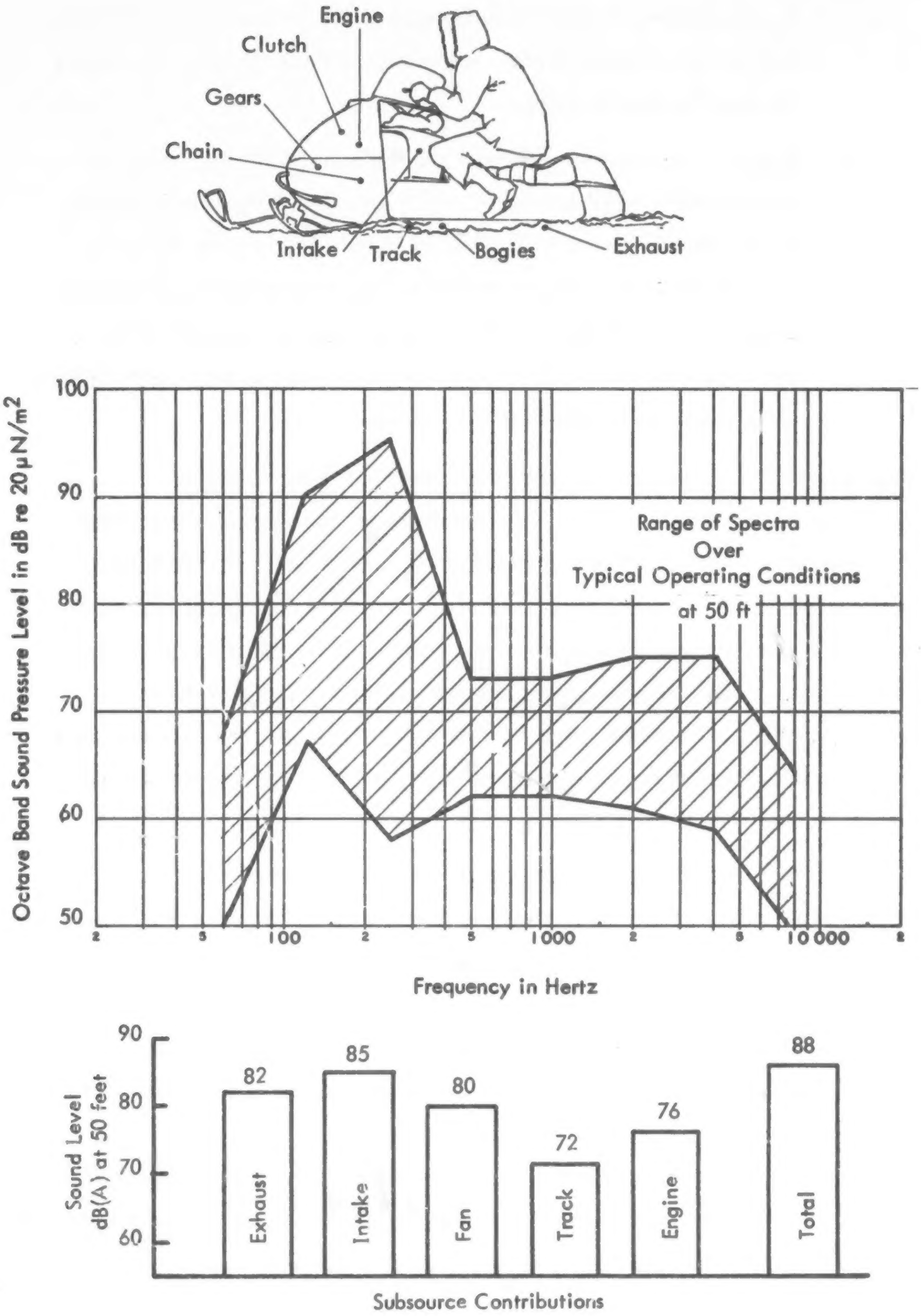


Figure 2.7-5. Snowmobile Noise

the application of quieting techniques to the internal engine structure, and cowling enclosures provide the only suitable and practical means for reducing engine noise.

- Intake – Most current snowmobile manufacturers do not silence the engine intake. Unfortunately, the intake is usually directed ahead of the operator and contributes significantly to his noise exposure. Some sacrifice in engine performance may be required to silence the intake system. However, little work has been done in this area, although some manufacturers are now producing accessory air-cleaner units which aid in reducing this problem.

Dune Buggies, ATV's (All Terrain Vehicles) and Other Off-Road Vehicles

The principal noise output of the remainder of those vehicles considered under the "recreation" classification is predominantly from the exhaust. Because of the unregulated nature of these vehicles and their use, the owners tend to attempt to achieve maximum power output through the use of tuned and straight-through exhaust (unmuffled) systems.[6] An example of typical spectra for a VW-powered dune buggy with a tuned "megaphone" exhaust system is presented in Figure 2.7-6.[20] Engine and intake noise are also quite apparent in these vehicles, but are on the order of 15 to 20 dB less significant than the exhaust.

2.7.3 Environmental Noise Characteristics

Except when several recreational vehicles are operating semi-continuously around motor recreation parks and high usage lakes, they provide only a minor contribution to the steady-state residual noise levels in the areas in which they operate. However, since the majority of these vehicles are operated in remote areas which have low residual noise levels, they can be heard as intrusive noises at much greater distances than would be expected in an urban area.[21]

Power boats are operated (by law) at least 100 feet from shore and usually well away from other boats, hence minimizing the levels at the shore and local community.

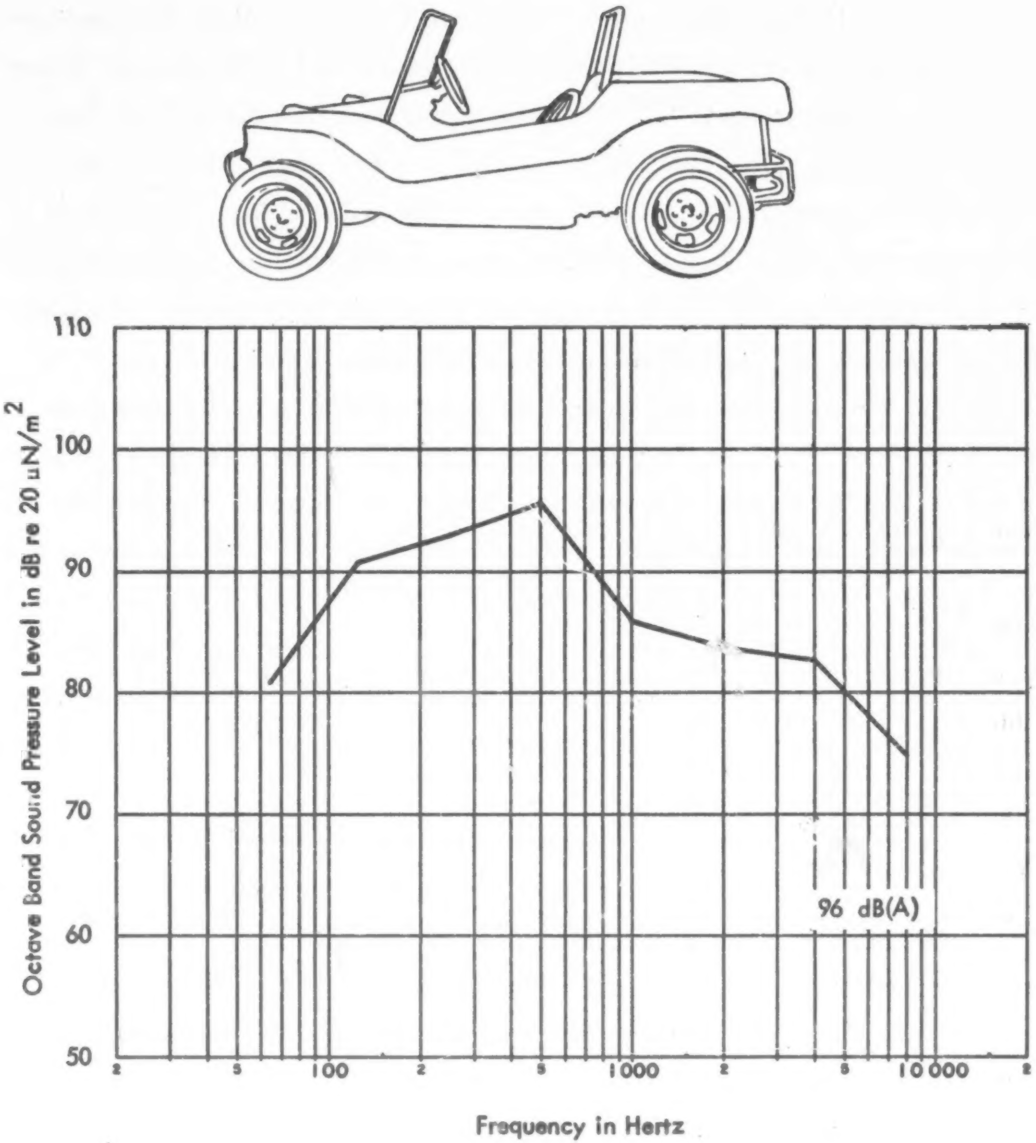


Figure 2.7-6. Typical Octave Band Spectra for V.W. Powered Dune Buggy Equipped with "Megaphone" Exhausts (Levels at 50 Feet)

Mini-bikes, a particularly annoying noise source in residential communities, are normally produced with a muffler which reduces their noise levels at 50 feet to the 75 to 80 dB(A) range.[16,22] The problems that arise from the usage of these machines (primarily by youngsters not old enough to obtain driver's licenses) stem mainly from their operation in the proximity of residential dwellings. The problem is further aggravated when the stock muffler is removed and replaced by an "expansion chamber" exhaust system which the owners feel contributes to the power.[6] The modified machines are then capable of levels of 85 to 90 dB(A) at 50 feet.[22]

The operator of most types of recreation vehicles is usually exposed to high noise levels for the duration of his ride. Typical levels for snowmobiles range to as high as 115 dB(A) under full throttle acceleration. Under cruise condition, the operator's noise level is often in the vicinity of 108 dB(A).[5,9,18] It is estimated that the average enthusiastic snowmobile owner uses his vehicle about 13 hours per week during the snow season.[3] The average duration per ride will probably range from 3 to 4 hours. It is assumed that this usage pattern is fairly typical for other types of recreation vehicles, including watercraft and motorcycles (90 percent of which are estimated to be pleasure vehicles).

The noise levels in outboard motorboats are also generally high. Typical levels range from 84 dB(A) for 6 horsepower units to 98 to 105 dB(A) for 125 horsepower units measured at the driver position under accelerating conditions.[9] At cruising speeds, operator levels on all boat types (inboard and outboard) range from 73 to 96 dB(A).[23] Operator levels on motorcycles also follow this trend of typically high levels with 115 dB(A) occurring on some unmuffled off-road cycles.[13]

A factor which should be considered in discussing operator noise exposure is the use of safety helmets. When properly fitted and used, they provide a significant reduction in noise levels at the operator's ear, as well as providing accident protection. There is no question that snowmobiles, many motorcycles, and some boats present a risk of permanent hearing damage to both operator and any passenger. Ear protective devices should be worn in these cases.

2.7.4 Noise Reduction - Industry Efforts and Potential

Figure 2.7-7 illustrates the present ranges of noise levels for recreation vehicles at both the observer at 50 feet and the operator positions. Also summarized in this figure are the near-term noise reduction potentials deemed achievable with current technology and the long-term noise reduction potentials which must result from further research and development efforts.

The recreation vehicle industries have incorporated some rather refined concepts into their products to achieve current noise levels. The greatest noise reduction has been accomplished through exhaust system treatment. Because nearly all snowmobiles, outboard engines, and a good percentage of motorcycles are powered by 2-stroke engines, a good deal of development and research has been done in quieting the exhaust systems on these devices. The expansion chamber exhaust system, which is considered essential for 2-stroke performance, has been muffled to a high degree with little loss of horsepower.[14,24] Engine shielding and isolation have been developed to a great extent on outboard motors and this technology is gradually being applied to snowmobiles. Excluding motorcycles, the industry as a whole has nearly reached the stage where exhaust treatment has been fully exploited, leaving further reduction efforts to be aimed towards intake silencing and engine noise itself. However, the motorcycle has yet to overcome its design constraints in packaging exhaust systems of sufficient size to provide greatly improved silencing; therefore, further research is required to achieve adquate silencing without imposing severe weight and size restrictions.

In the following paragraphs, current industry efforts in noise reduction and noise reduction potential will be discussed separately for pleasure boats, motorcycles, and snowmobiles.

Pleasure Boats

The outboard motorboat has the longest history of any of the products in the leisure vehicle field. The annoyance caused by noise from outboard motors was recognized by industry long before any legislative bodies began to act to control its effect. In the late 1920's and early 1930's, manufacturers motivated by public pressure

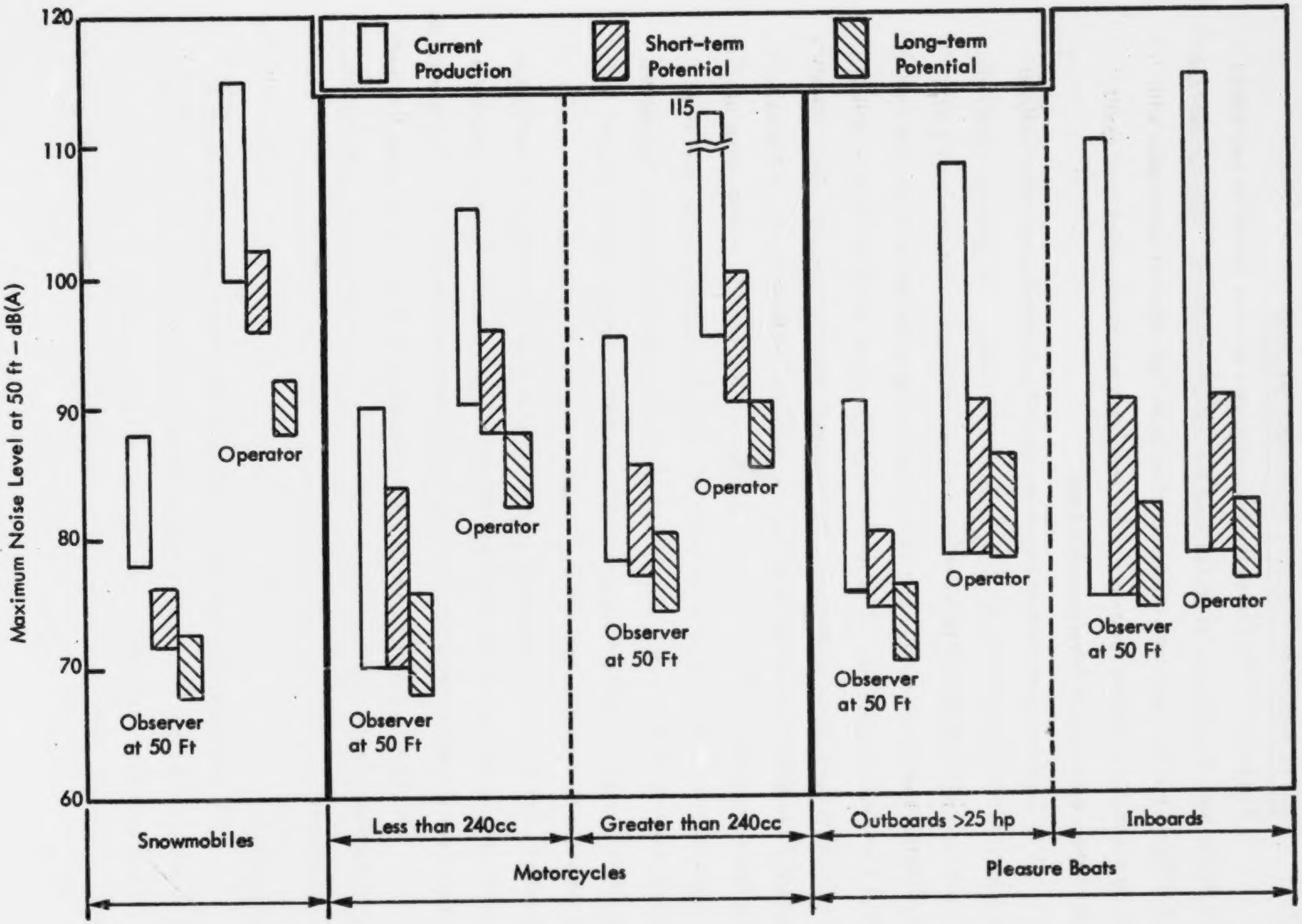


Figure 2.7-7. Potential Noise Reduction for Recreational Vehicles

began experimenting with underwater exhaust systems to reduce the noise output of these devices. Their success in the late 1940's was one of the factors which led to a dramatic growth market for motorboats. By the mid-1950's, more sophisticated quieting techniques were being incorporated, such as extensive vibration isolation within the engine and acoustically treated cowling on the engine.[25,26] The outboard engine has been continually refined up to its present state. The current outboard probably represents the quietest application of a 2-stroke engine for its power output on the market today.

The largest manufacturer of outboard engines produces a top-of-the-line 125-horsepower engine that produces maximum noise levels at 50 feet of 81.5 dB(A). The quietest model is rated at 6 horsepower and produces maximum noise levels of 64.5 dB(A) at 50 feet.[9] This same manufacturer feels that because of the company's efforts in producing quiet outboards, its percentage of the market has increased substantially until it is now the leader in outboard sales.[27] The major areas of complaint concerning pleasure boat noise are created by the large inboard-drive ski boats which incorporate dry stack exhausts (unmuffled and not exited under water). In addition, many inboard ski boats also incorporate the automobile "hot rod" techniques in achieving maximum horsepower from their engines. The engine is fully exposed, and in addition to unsilenced exhausts, usually has unsilenced carburetor intake as well. These machines produce noise levels at 50 feet of up to 112 dB(A). Noise output from the same configuration, with underwater exhausts, has been reduced to around 97 dB(A).[10] Many states are now moving to prohibit operation of these dry stack boats.

More refined inboard designs incorporate a silenced intake system and an acoustically treated full engine enclosure along with the underwater exhaust mentioned above. This type of ski boat will exhibit noise levels in the 85 to 90 dB(A) range at 50 feet.[10] Smaller engined inboard boats will fall in the 75 to 80 dB(A) noise level category.[8,9]

For pleasure boats, significant future noise reduction efforts should be primarily aimed at further reducing operator noise exposure levels. Crash helmets are seldom used by participants, except during race events, hence the noise levels in these pleasure craft must receive more attention.

Significant noise reduction can be accomplished in inboard designs due to the rather advanced state of acoustic enclosure design for items of this size. It is felt that for the majority of inboard designs, a long-term goal of 76 to 82 dB(A) is reasonable. Outboard engines (whose reduction potential is indicated in Figure 2.7-7 for models over 25 horsepower) pose a more difficult problem due to their design constraints which emphasize high power-to-weight ratios. It is expected that lower operator levels for outboard powered craft will only come through further efforts in intake silencing and either through revised internal engine design or bulkier engine enclosures. For outboard powered boats, an examination of current abatement technology indicates that operator noise levels in the range of 78 to 86 dB(A) constitute a reasonable long-term potential. Further, as a result of efforts to reduce operator noise exposure, non-participant levels at 50 feet should eventually be reduced to the range of 70 to 76 dB(A).

Motorcycles

The motorcycle also has a long history in the leisure field. Motorcycles, due to their design constraints of lightweight construction and maximum power output for a given displacement engine, have long been criticized for their excessive noise. The average motorcycle rider tends to associate noise with power and performance, and generally feels it fits the motorcycle "image". The major manufacturers have only recently taken steps to change these beliefs. Now all current production motorcycles intended for highway use must comply with state noise legislation. In addition, most major manufacturers, under the guidance of the Motorcycle Industry Council, have agreed to place mufflers on all their off-road motorcycles to limit their noise output to 92 dB(A) at 50 feet.[7] The industry is currently in the process of trying to convince the consumer that noise does not necessarily mean power. It feels that this is an essential step in preparing the consumer to accept the quieter, new generation machines that will, necessarily, weigh somewhat more and deliver less horsepower per cubic inch displacement.

The noise levels of current production motorcycles cover a fairly wide range among different manufacturers and among vehicles of varying engine displacement.[28,29] The majority of motorcycles are now meeting the 88 dB(A) maximum noise specification of various states; however, a number of the large displacement machines are unable to meet this criteria in their present designs.[29] Although the technology exists to produce quieter motorcycles, achieving further noise reductions will necessitate some design compromises on a majority of the models.[12]

The exhaust system is the major contributor to overall noise levels. Although exhaust systems can be designed to reduce this component's contribution to the 75 dB(A) range, significant packaging and weight limitations must be overcome.[14] Also, current motorcycles do very little to silence their intake systems, although almost all provide air cleaner devices. Silencing on the order of 10 dB is feasible if moderate restriction of intake air flow can be tolerated.

The most critical area yet to be tackled in motorcycle silencing is the engine and mechanical noise. Acoustic enclosures have not been found to be practical solutions on air-cooled engines. A number of attempts have been made at silencing individual engine noise sources, such as adding damping compound to timing gears, stiffening primary chain covers, positive oil feed lubrication of cam shaft bearings, and adding cross ties to the engine cooling fins. This attempt by one manufacturer yielded only an average reduction of 1.2 dB.[12]

Achieving the more restrictive noise level requirements for motorcycles that are forecast for the next 5 years will require major redesign of numerous components. Specific examples of solutions that may yield beneficial results include incorporation of journal rather than roller or ball bearings, timing chains rather than gears, more lubrication, stiffer structures and nonresonating materials for nonfunctional components. With these changes will undoubtedly come an unwelcome power loss. For example, one manufacturer reduced engine noise levels in laboratory experiments to 75 dB(A), but with a 15 percent power loss.[12] Cost and weight penalty figures are not available for this example.

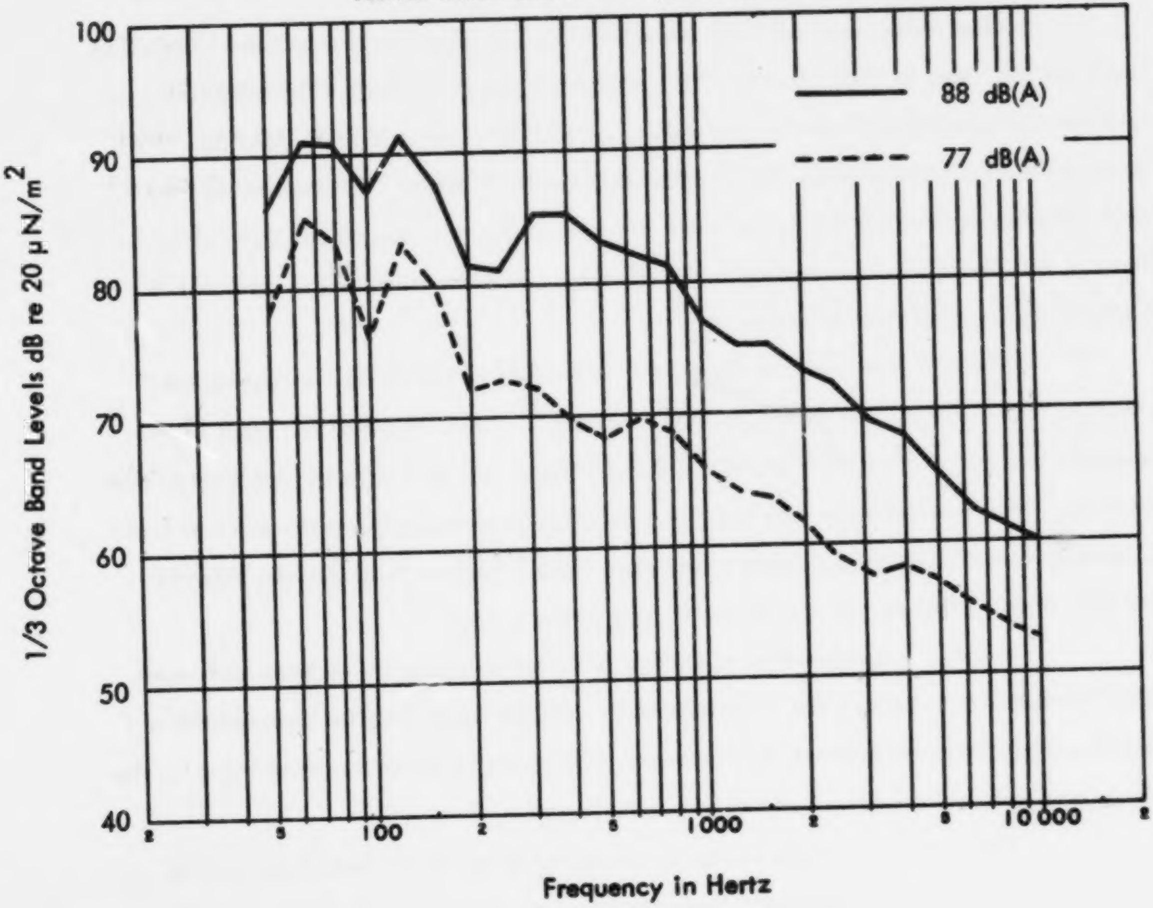
Figure 2.7-8 gives the spectra of two 750 cc 4-cycle motorcycles of different manufacture, but tested under identical conditions. The difference in the noise levels produced by the two vehicles is 11 dB.[29,30] The price of the quiet motorcycle is $1848 as compared to $1595 for the noisy machine. The quiet vehicle weighs 440 pounds versus 480 pounds for the noisy model. The relative horsepower ratings are 57 horsepower at 6400 rpm for the quiet machine as compared to 67 horsepower at 8000 rpm for the noisier vehicle. This example illustrates the compromises with which the industry and the consumer are faced in achieving reduced noise levels with current technology.

Motorcycles potentially face severe design modifications if their intruding effect upon the ambient noise environment is to be significantly reduced. Redesign of internal engine structure to provide the noise reduction achieved in laboratory experiments may be required to achieve a long-term potential of 75 to 80 dB(A) at 50 feet under maximum noise conditions. Additional attention must be given the engine intake system to reach these levels. It is assumed that technology will advance sufficiently to provide quieter intake and exhaust systems with minimized power loss and reduced package space requirements.

Operator levels should be reduced to the 85 to 90 dB(A) range as a result of the modifications listed above. Here again, the use of protective crash helmets would serve to greatly reduce the risk of high operator noise exposure.

Snowmobiles

Snowmobiles are a relative newcomer on the leisure vehicle scene. Since their introduction in 1958 as a low powered, lightweight, go-anywhere-in-the-snow-type vehicle, they have evolved into a more refined family-type recreation vehicle. The original concept called for a minimum of weight coupled with maximum performance for the engine size. Hence, the original snowmobiles possessed unshrouded



Comparison of Two Current Production 750 cc Four-Stroke Motorcycles Tested Under Identical Operating Conditions

Figure 2.7-8. Examples of Demonstrated Further Noise Reduction

engines and unmuffled (or poorly muffled) exhausts. Their rapid rise in popularity led to numerous consumer complaints about their excessive noise. As more vehicles were produced, consumers demanded higher and higher horsepower outputs until today, some snowmobiles are capable of nearly 100 mph.[5] Their effect on the noise environment has been compounded in many cases by the fact that some owners remove the factory-installed muffler systems in an attempt to achieve more power. In most cases, this actually results in less power and considerably greater noise.

The noise levels of 1971 models at 50 feet generally range from 15 to 20 dB less than the noise of 1961 models. This reduction clearly indicates the manufacturers' concern for the problem, and is impressive, particularly since prior to June 30, 1970, there were no effective snowmobile noise regulations in effect. Minnesota was the first state to require that the noise level of snowmobiles not exceed 86 dB(A) at 50 feet.[32] Most of this reduction has resulted from improved exhaust systems which actually improve engine life and performance.[14]

Exhaust treatments are currently available which utilize an expansion chamber incorporated into a tuned silencer system.[24] With this design, much of the acoustic energy is reflected back to the exhaust port, where it acts to supercharge the mixture. This configuration also creates a negative pressure pulse at the exhaust port to scavenge the spent gases. Such systems are more effective than straight pipes or mufflers alone, both for noise suppression and power output.[17]

Another consideration in muffler design is to place the exhaust exit away from the operator to reduce his noise exposure. Exhaust exits may be directed down into the snow or beneath the driver; however, care must be taken to avoid icing up the tracks and suspension by the blast of hot exhaust gases.

Other major considerations in achieving these levels have been in the areas of intake silencing and engine enclosures. The cowling configurations on the different brands of snowmobiles vary quite markedly. The lighter weight, price-competitive units generally use a minimal engine shielding, while the more luxurious multicylinder units are provided with much better shielding. The need for adequate engine cooling is a legitimate design constraint and the main argument against engine enclosure for most vehicle types. However, the snowmobile, by virtue of the environment in which it operates, is most ideally suited to a well-ventilated acoustic enclosure. In addition to reducing noise levels to the distant observer, the engine enclosure is perhaps the most significant factor in reducing the high noise levels experienced by the operator.

Further reduction is undoubtedly obtainable through more refined engine cooling methods which would allow more complete engine enclosure, some design modifications to allow rerouted intake through silencing devices, and more space for large volume mufflers.[5,14,33]

The major problem area left to be fully assessed is the operator noise environment. While earlier noise levels of 120 dB(A) and greater have been substantially reduced, current models still produce levels at operator position of 105 to 115 dB(A).[5,9] It is felt that the additional work on intake silencers and engine enclosures will do much to alleviate this problem. It is estimated that the current snow vehicles reflect a cost increase of about 15 percent to obtain their present noise levels.[9]

There are currently pending a number of noise laws which, if enacted, will attempt to limit the noise output of snowmobiles at 50 feet to 73 dB(A) in 2 to 3 years. One manufacturer is currently attempting to develop a machine to comply with this requirement. While specific details are not available concerning the techniques involved in achieving these levels, he has estimated that such reduction will carry with it a 15 to 30 percent increase in vehicle weight, and a corresponding 30 percent increase in price.[9] A number of the smaller manufacturers with limited or no research and engineering facilities may be unable to meet these requirements.

One of the major suppliers of mufflers for the snowmobile industry expressed the opinion that there exist currently available exhaust treatments which provide 30 to 35 dB attenuation.[14] This means a reduction in the contribution of the exhaust system from approximately 105 dB(A) unmuffled to the 70 dB(A) range.

This reduction can be accomplished with minor power loss but at the expense of some additional weight and space required for the muffler.

On the majority of current production snowmobiles, no intake air cleaners or silencers are used. It has been shown experimentally that a simple air cleaner assembly will reduce intake noise by 7 dB without impairing performance.[14] It would appear that further reduction in this area is possible, and reductions of 12 to 15 dB would be feasible with some power loss, thus reducing the intake contribution to approximately 70 dB(A) at 50 feet.

An example cited by one manufacturer is shown in Table 2.7-1.[14] It is felt that further overall reduction into the 75 dB(A) range is feasible with improved engine enclosures.

Table 2.7-1

Example of Further Noise Reduction Using Existing Technology

Noise Producing Component		1971 Model As Produced (dB(A) at 50 feet)	With Intake and Exhaust Treatment (dB(A) at 50 feet)
Exhaust		82	70
Intake (stock range 77 to 87 dB(A))		85 (bare stack)	78 (with silencer)
Cooling fan	Unmodified	80	80
Track & suspension		72	72
Engine/mechanical*		76	76
OVERALL		86 dB(A)	82 dB(A)

* Test vehicle had production engine cowling in place.

Future snowmobile noise output levels at 50 feet could be reduced to the 70 to 73 dB(A) range by 1980. This figure assumes significant advancement in noise reduction technology in a number of areas. The first step is to utilize existing exhaust systems, which reduce exhaust noise levels to the 70 to 75 dB(A) range.[14] Further refinement will be required to produce systems that are of reduced size and do not drastically affect power output. Intake system silencing should be advanced sufficiently by that time to also provide maximum intake noise levels in the 70 dB(A) range without significantly affecting engine performance. A key area of attenuation will be in more refined engine cooling and air ducting techniques that will allow the use of full engine enclosures, hence reducing this system's contribution to the 70 dB(A) range. The last significant system that must be further refined would be the drive track and suspension system. Current contribution from these elements is now estimated at around 72 dB(A).[14] It would appear that component isolation and slightly refined design will achieve adequate noise reduction in this region.

It is believed that these noise reduction techniques will greatly aid in reducing operator noise exposure levels. Rerouting the intake and shielding the engine should reduce these levels down to the 88 to 92 dB(A) range.[20]

3.0 Devices Powered by Small Internal Combustion Engines

3.1 Introduction

The noise emanating from equipment powered by small internal combustion engines is well known to millions of people, particularly those who maintain gardens or lawns. The total United States production of these engines was about 10.9 million units in 1969. This total includes all engines below 11 horsepower except those used for boating, automotive and aircraft applications.

Over 95 percent of these engines are air cooled, single cylinder models. The vast majority are 4-cycle, while the 2-cycle version comprises most of the remaining market. More than half of the single cylinder engines power the estimated 17 million lawnmowers in use today. The majority of the remaining engines are used in other lawn and garden equipment such as leaf blowers, mulchers, tillers, edge trimmers, garden tractors and snowblowers. In addition, about 750 thousand chain saw engines and 100 thousand engines for small loaders, tractors, et cetera, were produced in 1970, while agricultural and industrial usage together account for another 1.5 million engines. Generator sets, while not presently employing as large a number of engines, are an important consideration because of their growing numbers.[1,2]

The categorization of these devices by usage and typical noise levels is summarized in Figure 3-1.

3.2 Source Noise Characteristics

Generators

Of the 100,000 generator sets sold each year in the United States, most are used in mobile homes, campers, and large boats, where their electrical output is used to power air conditioning, lighting, and other equipment. These sets generally have 3 to 5 kilowatt capacity with a few units producing 8 kilowatts or more. Engine size is of the order of 2.2 horsepower per kilowatt, often with considerable derating of the engine for quiet operation so that the generator's noise may be tolerated by users and their neighbors over long periods of use.[3]

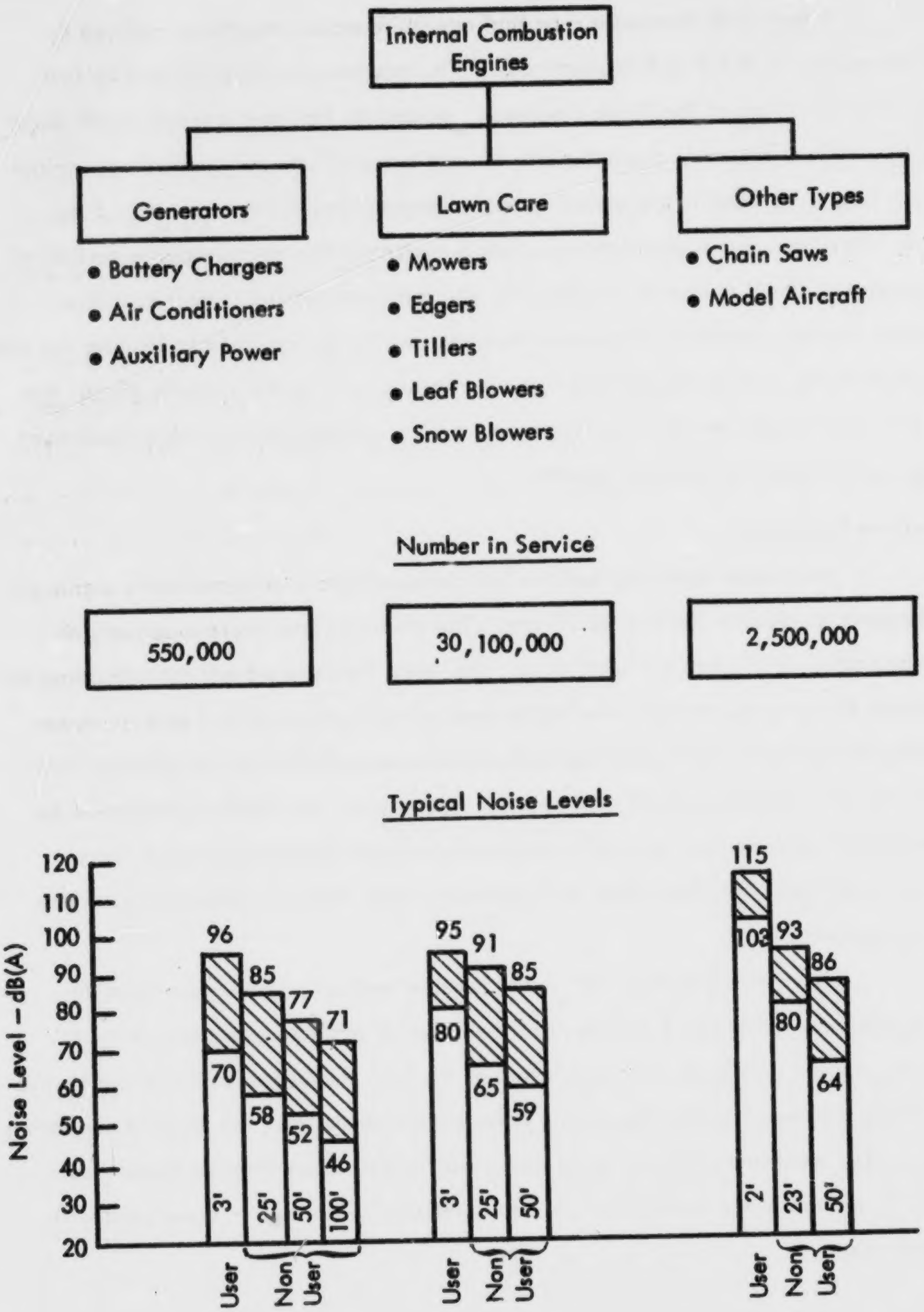


Figure 3-1. Characteristics of Devices Powered by Internal Combustion Engines

Figure 3-2 illustrates a typical one-third octave spectrum radiated by small generators of the 3 to 5 kilowatt size.[4] The spectrum is characterized by two peaks, one occurring at the firing frequency, around 40 Hz, and a second peak about 1000 Hz. This spectrum is characteristic of most types of internal combustion engines. The low frequency peak is associated with the fundamental firing frequency of the engine. However, the high frequency peak is generally the most annoying portion of the spectrum since it occurs at a frequency where human hearing is most sensitive. This peak may be attributed to acoustic radiation by the hot gas bubble leaving the exhaust with each firing, and to mechanical noise in the engine.[4] In the example given, the high frequency noise has been heavily suppressed in comparison with other equipment having less stringent noise requirements.

Lawn-Care Equipment

Lawn-care apparatus built in the United States is predominantly equipped with engines running at 3000 to 36000 rpm. The characteristic noise spectrum, as shown in Figure 3-3, has a double peak, the lower frequency peak corresponding to the engine firing frequency and the higher peak occurring from 2 to 3 octaves above the firing frequency.[4] Additional high noise levels are radiated by the rotating blade. In the case of a rotary mower driven by a 4-cycle engine, the blade passage will be 4 times the firing frequency and will merge with the high frequency engine noise. Equipment without a rotating blade will generally have other machinery noise of the same approximate level.

It can be shown that "A" scale measurements of engine noise from this class of engine is generally 2 or 3 decibels below an A scale measurement of the machinery noise.[5] However, the modulation of the high frequency engine noise by the lower firing frequency makes the engine noise more audible than the noise of a rotating blade or other machinery.[4] Thus, even heavy muffling on lawn-care equipment does not totally eliminate the audibility - or characteristic "putt-putt" - associated with this modulation.

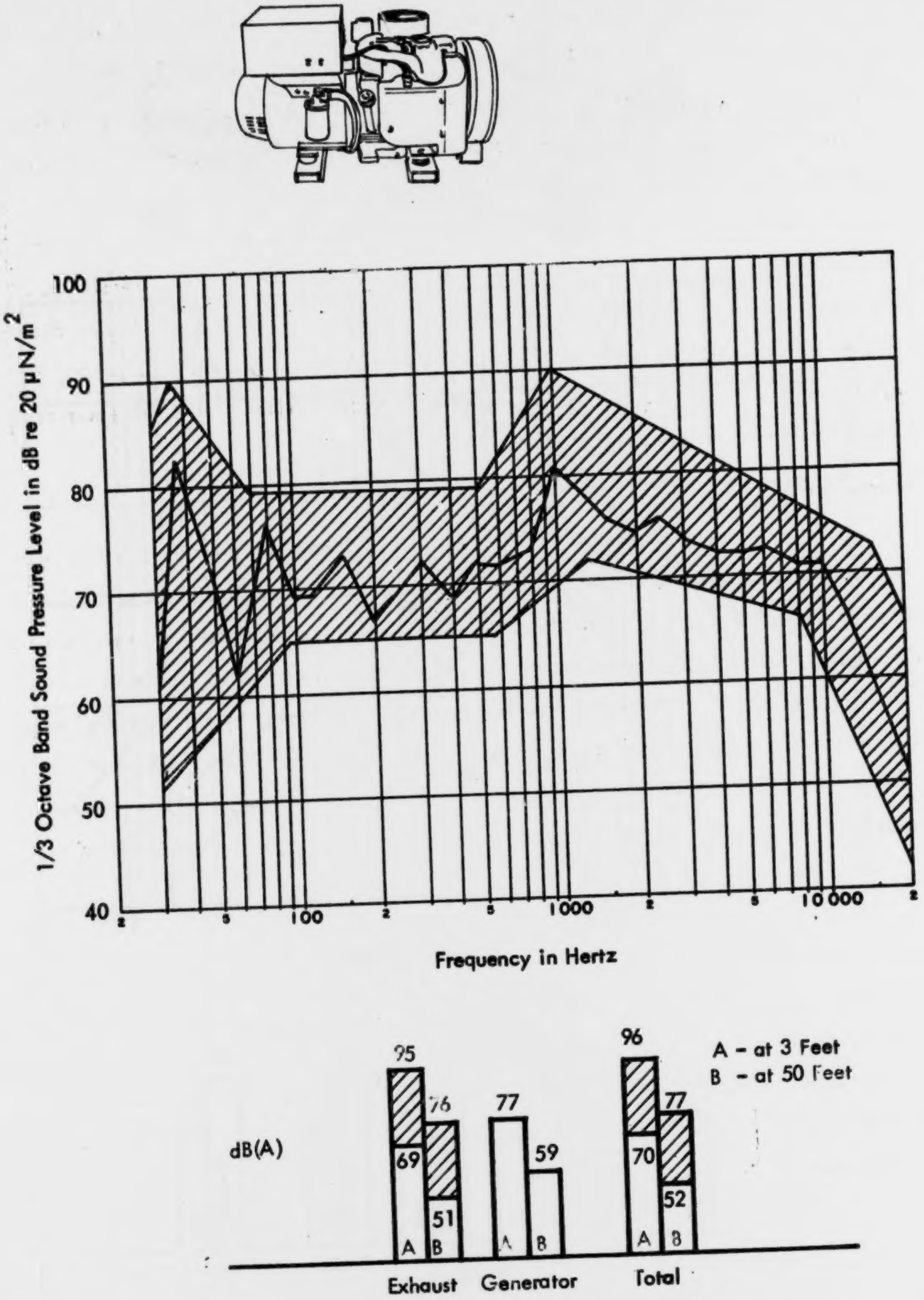


Figure 3-2. Typical Noise Characteristics of Generators

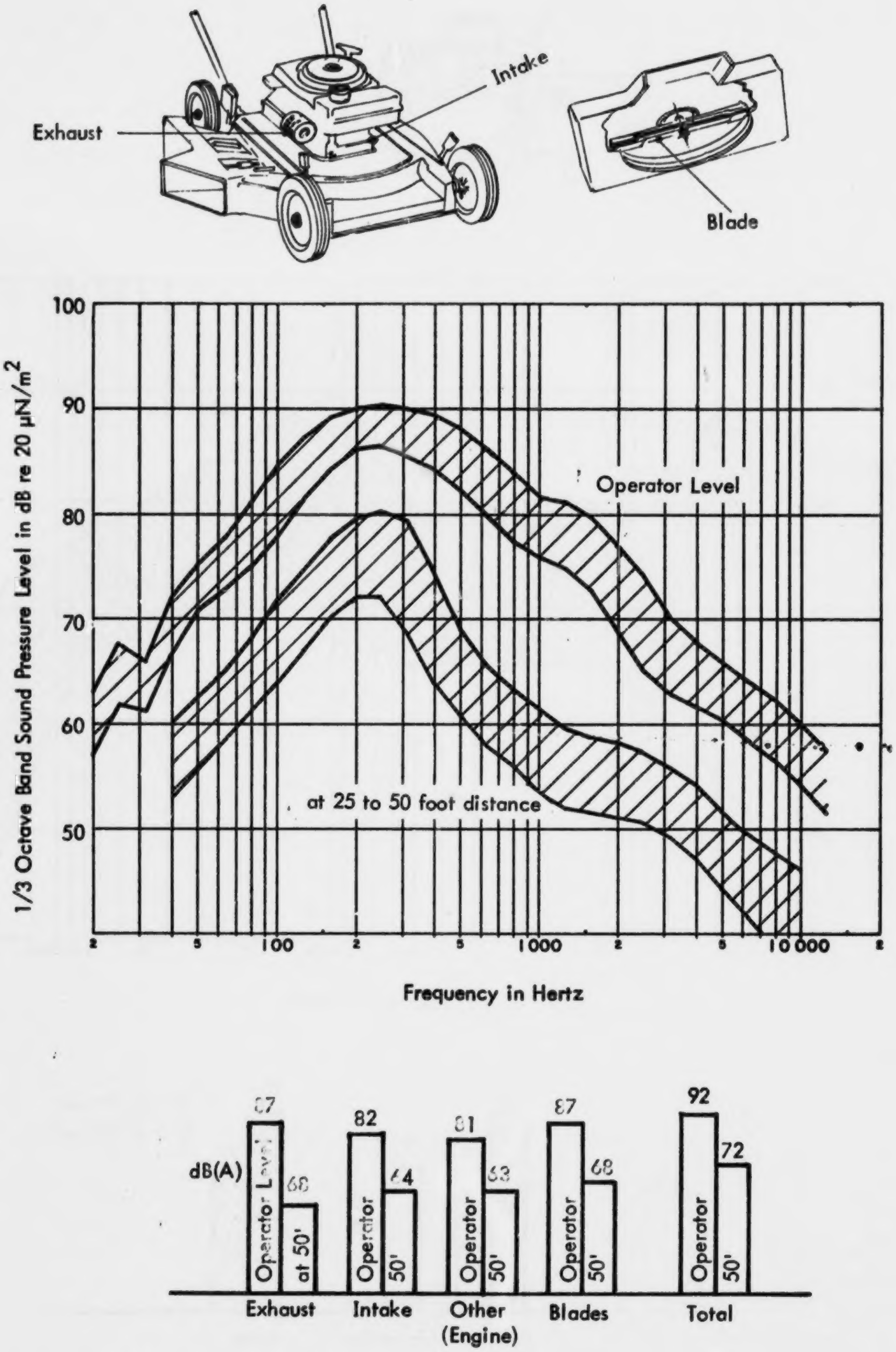


Figure 3-3. Typical Noise Characteristics of Rotary Lawnmowers

Chain Saws

A typical chain saw, designed for casual use, weighs from 6 to 20 pounds and has a blade from 1 to 3 feet long.[4] The engine produces 5 to 8 horsepower and has a life expectancy of 1000 to 2000 hours.[6] In order that a device this powerful may be made portable, the engine must have a high power-to-weight ratio.

Fuel consumption, muffling, and durability are secondary considerations even in the industrial machines, as design criteria dictate the use of high speed. A typical engine may operate at 9000 rpm at a firing frequency of the same rate, or 150 times per second. The engine incorporates a muffler, typically weighing less than a pound, which includes a spark arrestor to prevent fire. The very high firing frequency brings the direct exhaust noise well within the audible range, as shown in Figure 3-4.[4] The broad peak, characteristically found in these engines two octaves above the firing frequency, occurs around 1000 Hz, the region of greatest audibility in humans.

Thus, the requirement for a small but powerful device has resulted in designs in which the engine noise is in the frequency range of greatest audibility, and the muffler structure is as light and small as possible. This combination results in equipment which produces levels as high as 115 dB(A) at the operator's position, with levels of 83 dB(A) common at a 50-foot distance.[4,7]

Model Airplane Engines

Model airplane engines are normally rated by displacement in cubic inches and few figures are published in terms of horsepower. These engines range from 0.029 to 0.20 cubic inch displacement, and may exhibit up to 1.5 horsepower per cubic inch. The noise spectra shown in Figure 3-5 were measured on 0.049 cubic inch displacement engines which would probably produce 0.06 to 0.08 horsepower. Model airplane engines are 2-cycle types, turning at very high rotational speeds, typically 12 to 18 thousand rpm, resulting in a firing frequency above 200 Hz.[4]

Manufacturers have only recently incorporated any type of muffling. Figure 3-5 illustrates data taken on two identical engines of 0.049 cubic inch displacement.[4] One was equipped with a muffler and the other was not. The 200-Hz

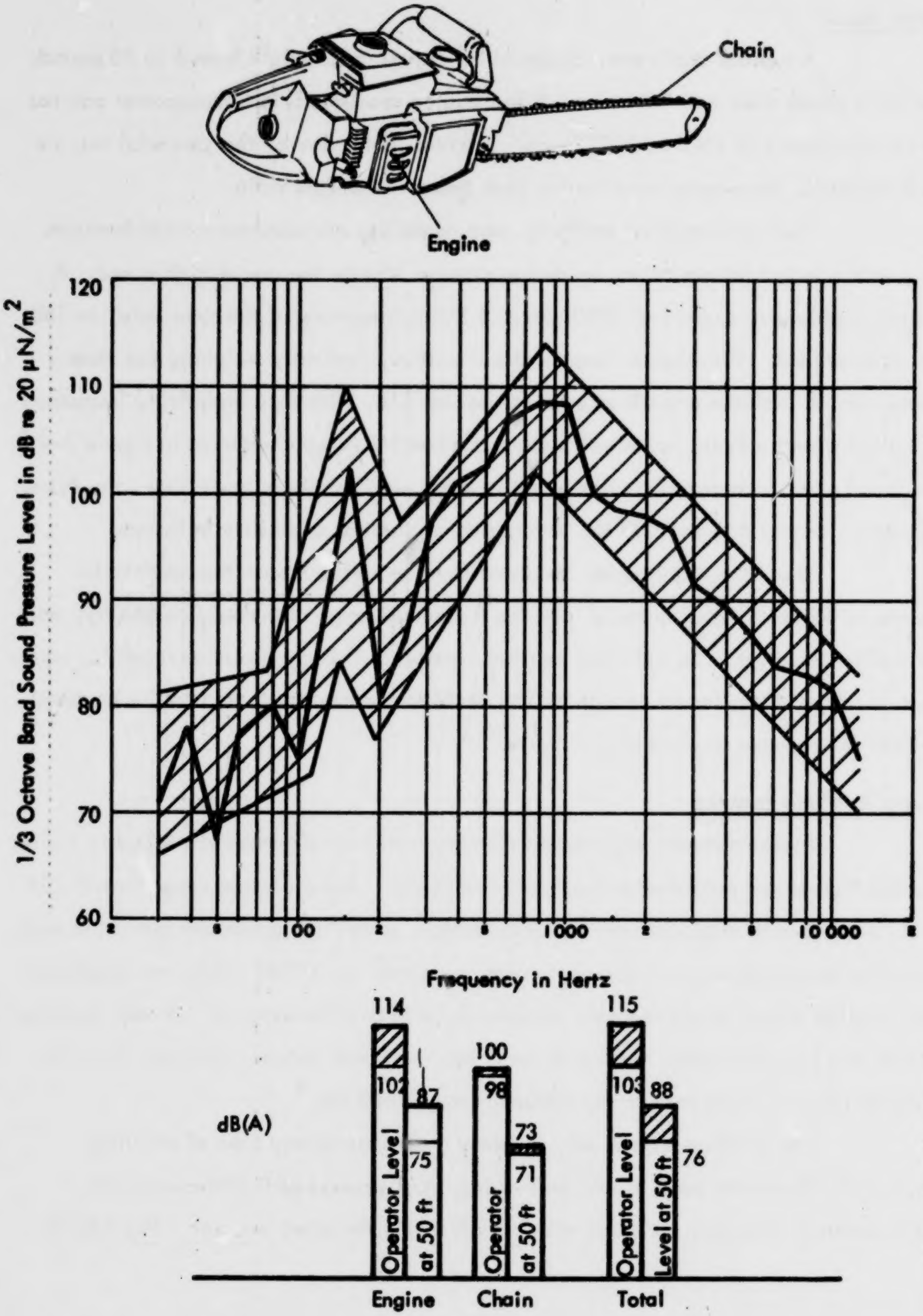


Figure 3-4. Typical Noise Characteristics of Chain Saws

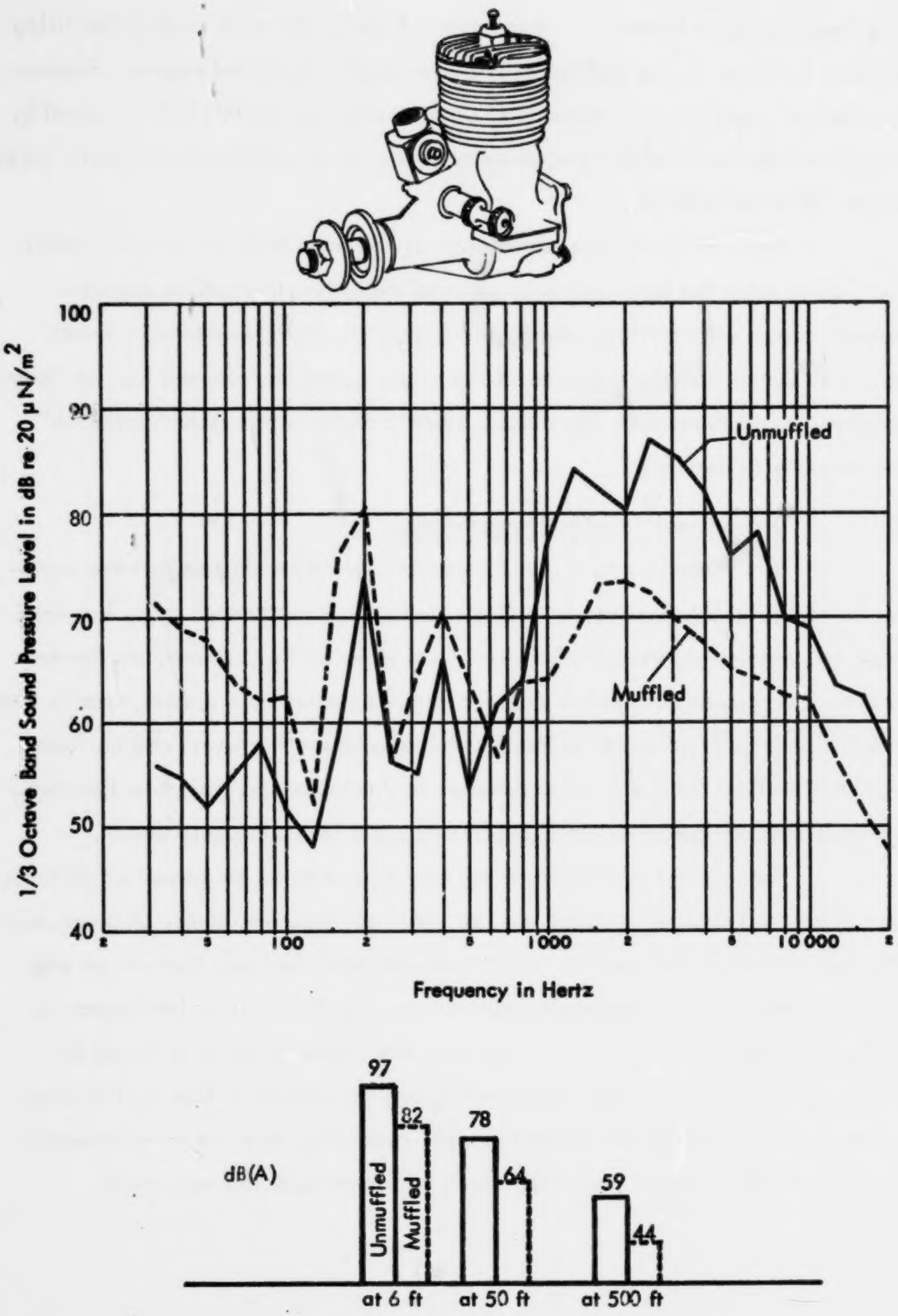


Figure 3-5. Measured Noise Characteristics of Muffled and Unmuffled Model Airplane Engines

firing frequency is in evidence in both cases. Indeed, the noise level at the firing frequency is higher for the muffled engine than for the unmuffled engine. However, since the "A" scale (and the human ear) discriminates against this 200-Hz signal by 10 decibels, the levels of this frequency are not quite as audible as are similar levels between 1000 and 4000 Hz.

Thus, the unmuffled noise levels at 1200 and 2400 Hz are considerably more audible when the bare engine is operated than when the muffled engine is operated. Even with muffling, the double peak frequency characteristic is very much in evidence, but the character of the engine sound has changed from an "angry mosquito" to something more like a noisy electric motor, while reducing the "A" scale noise by 12 decibels.[4]

3.3 Environmental Noise Characteristics

It is characteristic of small internal combustion engines that the equipment being powered is operated by a single person or is unattended. The low noise equipment, such as generators which have been well-muffled, operate unattended. However, the typical generator is used for supplying power to a camper, mobile home, or boat, and is built into a metal frame which also houses the owner and his family. When its vibrational energy is communicated to this frame, considerable annoyance may result even though its directly radiated acoustic levels are very low.[4]

The operator of lawn-care equipment attends the equipment at all times. Usage is generally during daylight hours in urban and suburban areas. A given user will operate a lawnmower for one or two hours per week and may then run an edge trimmer for approximately one-half hour. He may continue with a leaf blower to pick up the clippings and then use either a garden tractor or tiller in his garden. During such a hypothetical day, the operator may be exposed to four or five hours of noise in the high 80 to low 90 dB(A) range, depending upon the manufacturer's dedication to noise control and to the user's maintenance of the equipment.

Some other lawn-care equipment transports the operator, as in the popular riding mowers or garden tractors. Here the operator is directly behind or directly above the engine. The muffler and intake ports are generally somewhat closer to the operator's ear than the 6 feet characteristic of the push-type equipment. Also, equipment which can carry the operator generally requires a larger engine than would be required otherwise. These two factors combine to create considerably higher sound pressures at the operator's ear.[7] The A-weighted noise level for this situation generally ranges from the low to mid-90's, presenting the operator with a risk of permanent hearing damage when long periods of operation are endured each day, or when shorter time periods of operation are endured by a person who is especially sensitive to hearing damage.

A third type of engine characterized by high speed and minimal muffling is the chain saw. Operator ear levels for this device may be as high as 115 decibels, with quieter machines operating near 102 to 103 dB(A).[7,8] Such levels present a definite risk of permanent hearing damage, and use of ear protective devices should be recommended as a prudent precaution in the operating instructions and the labeling of such equipment.

The noise of model airplane engines and other small devices is usually not of a sufficient level to impose hearing damage risk on the user, during the short exposure times of close proximity to the engine.

A well-built generator will seldom exceed 70 to 72 A-weighted decibels at a distance of 50 feet when installed in a motor home or other such vehicle. It will not generally cause speech interference; however, when the generator is used during early evening and beyond, there may be considerable interference with sleep and relaxation to persons nearby. As the market for these devices expands, they will become a greater nuisance. Consequently, current production units are being improved as rapidly as technology and cost permit.

The non-participant noise environment generated by lawn-care equipment has at least some effect on a large portion of the population in the United States. This extensive effect is the result of the large numbers of engines being used in this application in heavily-populated areas. The equipment generates A-weighted noise levels in the low 70's at 50 feet and produces some speech interference. Where any kind of solid barrier exists between the source and receiver, a decrease of 5 to 15 decibels can be expected.[9] Thus, a solid wooden fence or the house itself will generally reduce the speech interference to acceptable levels. In many cases, the lawn-care equipment will not become a cause of complaint by the non-participant, as long as its use is restricted when people are sleeping and in early evenings when people are relaxing on their patios. In other cases, where a wire fence or no fence at all exists, complaints might well be forthcoming.

The non-participant environment generated by chain saws is fully capable of causing speech interference at distances of several hundred feet. Non-participants within 25 feet of the chain saw will be exposed to potentially damaging levels, as is the operator. The chain saw is not frequently used in areas of heavy population and is therefore not of frequent concern in the non-participant environment.[4] When it is used in populated areas, considerable reaction may be experienced from those exposed to the noise. It is probable that a reduction of the noise levels for the operator to the levels of lawn-care equipment would minimize problems in the non-participant environment. However, it must be recognized that a great deal of study would be required to accomplish this noise reduction within the cost, weight, and power considerations imposed upon chain saws by their preferred use.

In all cases of the non-participant environments mentioned, the persons affected will be in their homes or at other locations where they have gone for leisure time activities. Apartment dwellers are not exempt since the lawns around their apartments are mowed by larger, noisier equipment. Children attend schools where lawns are mowed, and even most hospital rooms are within earshot of a lawnmower.

Generators and chain saws both have a small effect on the general community since they are used outside populated areas. Chain saws affect the operator and helper at levels between 90 and 110 dB(A) with the operator receiving the highest levels. When this equipment is used in populated areas, all persons within 500 feet will generally be annoyed. However, duration is short and occurrence is infrequent so that their total impact is small. It is estimated that fewer than 5 million people per year will be adversely affected by these devices.

Generators affect their half-million owners plus another 1.5 million family members. In addition, each generator may annoy two other families, bringing the total number of persons affected to 12 million, roughly 5 percent of the population.

The non-participant environment for model airplanes can range from 78 dB(A) for nearby planes to 40 or 50 dB(A) at distance. Audibility is present at distances of many hundreds of feet. When short flights are made during daylight hours, annoyance is small. When flying is continuous or is conducted when people are relaxing outdoors, annoyance becomes great.

3.4 Industry Efforts Towards Noise Reduction

Historically, noise reduction has not been of primary consideration to the manufacturers of small internal combustion engines although unmuffled equipment has not been produced for many years because of buyer resistance to an excessively noisy product. Public tolerance, combined with some noise control, has produced a compromise situation between the consumers and the manufacturers.

Generally, noise reduction achieved by the engine manufacturers has resulted in engines which make somewhat less noise than the equipment they are designed to power. However, equipment manufacturers are not completely convinced of this conclusion, and tend to attribute the noise of the entire unit to the engine.

This situation is particularly characteristic of the small equipment manufacturer who purchases the engine from an outside source, having no involvement with engine design. In this category are large numbers of lawn-care equipment units which are constructed of pressed sheet metal in production shops around the country.

Many of the manufacturers of internal combustion engine powered equipment feel that they are being placed in the difficult position of being required to meet several divergent nuisance laws. These laws have been promulgated by various individual cities and towns, where noise restrictions are related to local economic and social conditions. This situation is typified by the experience of the manufacturers of lawnmowers. The recently enacted ordinance for the City of Chicago lists a descending scale for allowed noise for lawnmowers over the next few years which most manufacturers interviewed agree is realistic, and they are working toward compliance within the allotted time.[10] However, in the recent ordinance enacted by the City of Minneapolis, the equipment is not allowed to exceed certain ambient levels at the property line by more than 6 decibels.[11] Lawn care equipment is specifically exempted from these requirements, but is restricted to operation between the hours of 7:30 a.m. to 9:00 p.m. on weekdays, and 9:00 a.m. to 9:30 p.m. on Saturdays, Sundays, and holidays. If the lawn-care equipment can comply with the specified ambient requirements, then it may be used during any hours.

Other cities around the country have ordinances with noise levels as low as 40 dB(A) at the property line.[12] Although there does not appear to be a strong effort to comply with or enforce this latter ordinance, no manufacturer can look with impunity upon such a law, and he might even decide not to market in that area. As other localities pass noise ordinances, such inequities could proliferate, making the manufacturers' task much more difficult.

The extent of noise reduction within the industries supplying small internal combustion engines has been directly related to its effect on sales and the existence of noise ordinances. With the exception of the small generator industry, public pressure has not been sufficient to produce significant noise reduction efforts in most of these devices.

As a result, noise abatement programs have not been consistent. For instance, one manufacturer has demonstrated that a small generator, using a 3 horsepower engine with a vertical shaft housed within a complete enclosure, may be quieted to 70 decibels at a position 6 feet from the engine. If this same treatment were applied to a lawnmower, it would achieve an improvement of approximately 20 dB over most current production lawnmowers, and would make the engine quite inaudible in the presence of a rotating blade. However, no serious plans are being made for production of such a mower because of the high cost of the noise reduction treatment.

Another manufacturer is presently producing a lawnmower operating at a noise level of 50 dB(A) at 50 feet. This is some 13 decibels below the average machine and is accomplished through the use of a 2-cycle engine with a large muffler, and cast frames where pressed steel was previously used. Only 10 percent of the engines manufactured in the United States are of the 2-cycle type, so that a changeover to that type of engine from the present majority of 4-cycle types would be a very long and expensive task. High fuel cost could also create resistance in the marketplace.

Some manufacturers were questioned as to the feasibility of producing 2-cylinder engines for use in lawn-care equipment and other such devices.[3] This change from the single-cylinder engine has the advantage of allowing the exhaust pulse from one cylinder to partially cancel the pulse from the other cylinder. While many manufacturers admitted the feasibility of this concept, estimates of cost for such engines ran from 30 percent to 50 percent higher than the single-cylinder engines for a given horsepower rating. Such a penalty would make the "quiet" engines noncompetitive with the lower-priced models of current design.

Chain saw manufacturers recognize the existence of a serious noise problem with their equipment. The high power-to-weight ratio necessary in a device that must be hand-carried and be capable of quickly cutting trees and large brush requires a structure not capable of containing its own noise. Further, the noise produced by the chain itself is of the order of 100 dB(A) at the operator position and reduction of the engine noise below this level would not reduce total output to an acceptable level. In addition, where experimental prototypes have been built using electric motors to achieve very low engine noise, the more apparent mechanical noise of the chain gives the impression of a device "ready to fly apart," causing operators to resist using it.[6] Some experimental work is being done to reduce the noise of the chain, but cost limitations rapidly become prohibitive when exotic materials are used to damp the response of the blade to the chain.

Considerable engineering work has been expended to make the mufflers more efficient within weight and size limitations, and some success has rewarded these efforts. Sound levels have been reduced to as low as 103 dB(A) by some special mechanical devices with power losses of no more than 10 to 12 percent.[6]

Noise control within the industry served by small internal combustion engines will be affected by various laws and ordinances as enacted by the government bodies concerned. However, there will always be difficulty in encouraging noise abatement until public education advances to the point where the charisma of noise is gone. The motorcyclist who removes his mufflers to obtain more power may well degrade his performance and still feel he has gained power and status. He has his counterpart in the backyard garden. This man may remove the muffler from his tiller in order to dig his garden faster (he thinks). He may not remove his lawnmower muffler, but as it becomes old and less efficient, he may rationalize that the lessened back pressure will tend to compensate for losses of power through aging of other parts of the engine.

Whatever the basis for associating loud noise with productivity, an educational program is required to reduce public acceptance of noise. When each person is convinced that his contribution to noise reduction is meaningful, he may go to the manufacturer of the quietest machine, even if the cost is higher, and may take pride in his accomplishment. When this happens, as it has in the small generator field, manufacturers will probably respond decisively toward reduced noise levels. Interviews have shown that most manufacturers can respond, but, at the present time have found little market for quiet products when the public is asked to pay a premium for the quiet product.

3.5 Noise Reduction Potential

The combined effort by the public in demanding quieter products powered by internal combustion engines and successful response to this demand by the manufacturers, should provide a substantial decrease in annoyance from this equipment. This reduction in annoyance of intruding noise from lawnmowers, chain saws, et cetera, will be the principal benefit of a broad noise reduction program for devices powered by internal combustion engines. The estimated potential noise reduction that might be expected in the future for these devices is summarized in Table 3-1. The noise reduction values are relative to current noise levels and are specified in terms of potential reductions that can be achieved by the 1975, 1980 and 1985 time periods.

Full accomplishment of these noise reductions would largely eliminate annoyance problems in residential areas associated with use of lawn care equipment. However, the noise reduction potential for chain saws using existing technology is not sufficient to eliminate their annoyance problems or hearing damage risk for operators. Further noise reduction research is called for with these unique devices.

Table 3-1

Estimated Noise Reduction Potential for Devices
Powered by Internal Combustion Engines

Source	Noise Reduction, dB *		
	1975	1980	1985
Lawn Care Equipment	10	13	15
Chain Saws	2	2	5
Generator Sets	5	7	17

*Noise reduction relative to typical current noise levels in dB(A) at 50 feet.

4.0 ENVIRONMENTAL IMPACT FOR TRANSPORTATION VEHICLES AND SMALL INTERNAL COMBUSTION ENGINES

The preceding chapters have illustrated the nature of the noise characteristics as well as an estimate of current and future noise reduction potential for each major element of the transportation system and for small non-industrial internal combustion engine powered devices. With this background, one would like to have an overall view of the impact of these noise sources on the observer in a community and on the operator or passenger. As with any complex situation, several viewpoints are desirable in order to obtain such an overall perspective.

First, a simplified overview of the relative contribution of each of the source categories is provided by comparing their estimated daily outputs of acoustic energy. Next, the sources are compared to estimate their relative contributions to the outdoor residual noise level in average urban residential areas. Third, the sources are reviewed with respect to their individual single event intrusive characteristics, and their potential impact in terms of community reaction. Finally, the operator/passenger noise environment is reviewed with respect to the potential hazard for hearing damage and speech interference. Each of these comparisons is examined in terms of today's situation and in terms of one possible estimate of the potential change in the future. This example of a possible estimate of future noise helps to provide some insight into potential changes in the relative impact of the various source categories that could be effected with current or advanced technology.

A detailed discussion of the methods and sources of data used in carrying out this impact analysis is presented in Appendix B. Key assumptions utilized are summarized as follows.

- The impact analysis is based on current figures for the number and use pattern of the noise sources as determined from nationwide statistical data.[1] These data, coupled with the definition of characteristics of the noise sources, provided the basis for evaluating noise impact for 1970 in statistically-average communities.

- To project changes in the noise impact to the year 2000, a conservative model was chosen for growth of the transportation system and growth in numbers of internal combustion devices. Major assumptions for the model included (a) conservative population growth of 1.15 percent per year from 1970 to 1985 and 1.05 percent thereafter, and (b) conservative estimates for numbers of noise sources with growth rates approaching estimated urban population growth rates by the year 2000.[1]

- The potential change in noise levels for transportation vehicles and internal combustion engine devices has been estimated for three possible options for future noise reduction:

  Option 1 – No change in source noise levels after 1970. This represents a base-line condition wherein changes in noise impact would be due only to changes in number or use-patterns of the noise sources.

  Option 2 – Estimated noise reduction that would be achieved by extrapolating current industry trends by the year 1985, with no further reductions thereafter. This option assumes no new noise control regulations by local, state or Federal agencies, or any change in consumer demand for quieter vehicles.

  Option 3 – Example of projected noise reduction achieved by implementation of an incremental regulatory program to achieve a specified amount of noise reduction by the years 1975, 1980, and 1985. The criteria used for defining these estimates for potential noise reduction under this option example are as follows:

- By 1975, what noise reduction could be achieved by reducing levels to those for a typical quieter model now on the market.
- By 1980, what noise reduction could be achieved that industry has already demonstrated can be accomplished.
- By 1985, what is a practical limit for the potential noise reduction that could be achieved utilizing, if necessary, advanced technology.

The estimates of potential noise reduction utilized for Option 3 are summarized in Table 4-1 for the major transportation categories and in Table 4-2 for Internal Combustion Engine Devices.

Due to the very different use-patterns for transportation vehicles in contrast to non-industrial stationary internal combustion engine devices, it is desirable to evaluate their impact separately. Transportation vehicles are considered first.

4.1 Total Noise Energy Output per Day for Transportation Systems

A small, but no longer insignificant, byproduct of the growth in transportation is the conversion of a tiny fraction of the mechanical energy expended by the industry into sound — normally an unwanted sound or noise. For example, to propel 87 million automobiles and 19 million trucks and buses in the United States, an energy equivalent to approximately 7800 million kilowatt-hours is consumed every 24 hours — approximately one-third of the total energy consumption in the United States from all sources of power. Approximately one-millionth of this portion for transportation is converted into noise. The amount of noise energy per day for each element of the transportation system is a function of its noise level, number of units, and number of hours per day operation. Thus, a source category which has high noise levels, but only a few units in operation, can produce the same total noise energy per day as a source category which has a lower noise level but a very large number of units in

Table 4-1

Example of Potential Noise Reduction for Externally Radiated Noise for Transportation System Categories

Source	Effective Date		
HIGHWAY VEHICLE[1]	1975	1980	1985
Medium and Heavy Duty Trucks	3	8	10
Utility and Maintenance Vehicles	3	8	10
Light Trucks and Pickups	2	5	8
Highway Buses	3	8	10
City and School Buses	2	5	8
Passenger Cars (Standard)	2	4	5
Sports, Compact, and Import Cars	6	8	9
Motorcycles (Highway)	2	7	10
AIRCRAFT			
Commercial – with Turbofan Engines[2]	4	7	10
General Aviation – Propeller[3]	0	5	10
Heavy Transport Helicopters[3]	0	5	10
Medium Turbine-Powered Helicopters[3]	5	12	17
Light Piston-Powered Helicopters[3]	10	15	20
RAILWAY[1]			
Locomotives and Trains	0	5	8
Existing Rapid Transit and Trolley Cars	5	10	15
RECREATIONAL VEHICLES[1]			
Snowmobiles	10	12	14
Minicycles and Off-Road Motorcycles	2	7	10
Outboard Motorboats	2	4	6
Inboard Motorboats	5	6	7

[1] Relative reduction in average noise levels in dB(A) at 50 feet.

[2] Relative reduction in EPNdB at FAR-36 Measurement Position for Takeoff.

[3] Relative reduction in EPNdB at 1000 feet from aircraft during takeoff.

Table 4-2

Estimated Noise Reduction Potential for Devices
Powered by Internal Combustion Engines*

Source	Effective Dates		
	1975	1980	1985
Lawn Care Equipment	10	13	15
Chain Saws	2	2	5
Generator Sets	5	7	17

*Noise reduction relative to typical current noise levels in dB(A) at 50 feet

operation. Although this energy comparison does not relate directly to impact on people, it does identify and give some perspective to the major noise sources.

Table 4-3 summarizes the estimates of the A-weighted noise energy generated throughout the nation during a 24-hour day, by each category of the transportation system as it exists today. The top ten transportation categories, as ranked by their noise energy, constitute 96 percent of the total, and of these, heavy trucks and 4-engined aircraft alone produce over 50 percent of the noise energy.

The approximate A-weighted noise energy expended per day has also been estimated for the year 2000 for most of the surface transportation categories except aircraft for each of the three options defined above. The results are summarized in Table 4-4. The estimated value for 1970, specified earlier, is listed in the first column for reference. The second column, based on Option 1 (no noise reduction), shows the increase in noise energy per day due solely to the estimated increase in number and usage of sources. The third and fourth columns show the estimated trend in noise energy by the year 2000 for Option 2 (current industry trends) or Option 3 (possible noise regulation).

With the Option 3 noise reduction program, the noise energy by the year 2000 for all categories is always less than 1970 values. The reduction for Option 2 relative to Option 1 by the year 2000 reflects the current effort by the

Table 4-3

Estimated Noise Energy for Transportation System Categories in 1970

Major Category		Noise Energy (Kilowatt-Hours/Day)
Aircraft	● Commercial – 4-Engine Turbofan	3,800
	● Commercial – 2- and 3-Engine Turbofan	730
	● General Aviation Aircraft	125
	Helicopters	25
Highway Vehicles	● Medium and Heavy Duty Trucks	5,000
	● Sports, Compact, and Import Cars	1,000
	● Passenger Cars (Standard)	800
	● Light Trucks and Pickups	500
	● Motorcycles (Highway)	250
	City and School Buses	20
	Highway Buses	12
Recreational Vehicles	● Minicycles and Off-Road Motorcycles	800
	Snowmobiles	120
	Outboard Motorboats	100
	Inboard Motorboats	40
Rail Vehicles	● Locomotives	1,200
	Freight Trains	25
	High Speed Intercity Trains	8
	Existing Rapid Transit	6.3
	Passenger Trains	0.63
	Trolley Cars (old)	0.50
	Trolley Cars (new)	0.08
	Total	~ 15,000

● Top ten categories which each generate at least 125 kilowatt-hours per day.

Table 4-4

Example of Estimated Future Change in Noise Energy for Major Surface Transportation System Categories with Three Options for Noise Reduction

Source	Noise Energy in Kilowatt-Hours/Day			
	1970	2000		
		Option*		
		1	2	3
HIGHWAY VEHICLES				
Medium and Heavy Duty Trucks	5,000	10,000	4,000	800
Sports, Compact, and Import Cars	1,000	2,500	1,600	250
Passenger Cars (standard)	800	1,200	800	400
Light Trucks and Pickups	500	1,000	400	160
Motorcycles (Highway)	250	800	320	80
City and School Buses	20	20	8	3
Highway Buses	12	12	5	1.2
RECREATION VEHICLES				
Minicycles & Off-Road Motorcycles	800	2,500	NA	250
Snowmobiles	120	400	NA	16
Outboard Motorboats	100	160	NA	40
Inboard Motorboats	40	63	NA	12
RAIL VEHICLES				
Locomotives	1,200	1,200	1,200	200
Existing Rapid Transit	6	10	6.3	0.5

NA – Not available.

*Option 1 – No noise reduction.
2 – Estimated industry trend in noise reduction.
3 – Example of possible incremental program of Noise Regulation.

various industries to achieve a quieter product, while the additional reduction indicated for Option 3 shows the significant additional benefit that could be obtained through noise regulation.

These values of noise energy provide a rough indication of change in the relative magnitude of potential noise impact from transportation vehicles. By the year 2000 the noise energy values in Table 4-4 indicate a 100 percent increase from those in 1970 if no further action were taken to reduce noise (Option 1). Assuming current industry trends are continued (Option 2), there is little significant change in estimated noise energy indicated by the year 2000. Thus, the estimated noise reduction just offsets the increase in numbers of vehicles. However, by implementation of a positive regulatory program (Option 3 example), the aggregate noise energy per day for these sources in the year 2000 might be approximately 78 percent less than the current amount.

4.2 Contribution of Transportation System Components to the Residual Background Noise Level in an Average Community

As discussed in Reference 2, the residual noise level in a community is the slowly changing nonidentifiable background noise which is "always there" whenever one listens carefully outside the home. This residual noise level is originated by all forms of traffic moving throughout the community, and the large number and variety of stationary sources in a community, such as dispersed industrial plants or multiple air conditioning systems. The method for predicting this residual noise level is discussed in Appendix B.

Table 4-5 summarizes the estimated daytime residual noise levels for 1970 for each significant type of highway vehicle that operates in an average urban community. It is apparent that automobiles and light trucks are the principal sources which control the contribution to the residual noise level from transportation sources.

The average residual level was also predicted with the same technique for the years 1950 and 1960. The estimated values for the typical urban community are:

- For 1950 – Daytime Residual Level (L_{90}) $\approx$ 45 dB(A)
- For 1960 – Daytime Residual Level (L_{90}) $\approx$ 46 dB(A)

Table 4-5

Predicted Contributions to Daytime Residual Noise Levels By Highway Vehicles for a Typical Urban Community in 1970

Source	Approximate Source Density Units/Square Mile	Residual Noise Level dB(A)
Passenger Cars (Standard)	~ 50	43
Sports, Compact, and Import Cars	~ 20	41
Light Trucks and Pickups	~ 20	42
Medium and Heavy Duty Trucks	~ 1.5	33
Motorcycles (Highway)	~ 1	18
City Buses	~ 0.8	15
Total (All Vehicles)		47 dB(A)

These estimates indicate an increase over 10 years of approximately one dB in the residual level (L_{90}). This conclusion is consistent with the available measurements which are summarized in Reference 2. Although these estimated values for the residual level are certainly no more accurate than ±3dB, they agree very well with the available data and clearly indicate the prime sources of the residual noise in a typical urban community.[2]

Although the average residual level (L_{90}) in an urban community may not have changed significantly over the past two decades, the residual noise level in any given neighborhood may have changed. Such change is expected in neighborhoods where the land use has changed or where new service arterials (highway or freeway) have been developed. Thus, the development of rural land into suburban communities has increased the residual level, as has the construction of a freeway through an existing fully developed community.

The same model for estimating residual noise levels for 1970 has been applied to forecast trends for 1985 and 2000 as a function of the noise reduction options for highway vehicles only. The result of this projection, including the estimated residual levels for 1950 and 1960, is shown in Figure 4-1. The trend for Option 1 is clearly an upper bound, and indicates an additional growth of about 2.5 dB in the residual level in an average community by the year 2000 due solely to growth in the number and density of the noise sources. The lowest line (for the Option 3 example) represents the cumulative effect of achieving the 3-step noise reduction values summarized in Table 4-1. It estimates a net reduction in average residual noise level of 5 dB relative to today by the year 2000, whereas little change is forecast by the year 2000 for the projection of current industry trends (Option 2).

In summary, therefore, if no further action were taken to reduce noise levels of highway vehicles, the residual noise level in an average urban residential community would be expected to increase an additional 2 to 3 dB by the year 2000 over today's levels. On the other hand, a positive program of noise reduction for highway vehicles could prevent such an increase and achieve a desirable and reasonable reduction in average residual noise levels of about 5 dB over the next 30 years, not including any additional noise reductions to be achieved after 1985.

4.3 Relative Annoyance Potential of Intruding Single Event Noise

As discussed in Reference 2, the reaction of a community to excessive noise is the summation of annoyance from successive intruding single event noises such as aircraft flyovers or many cars driving by. It is desirable, therefore, to rank transportation noise sources according to their noise levels at a fixed distance, or, as illustrated in Figure 4-2, define the distance from the source within which the single event noise is greater than a specific value.

Two measures of the noise level are useful for this comparison; the maximum noise level which occurs when the vehicle passes by, and the single event noise exposure level (SENEL)* which integrates the A-weighted noise throughout the entire passby. This latter measure accounts for both noise level and duration, both of which have been found to be factors in annoyance. An SENEL of 72 dB has been chosen as

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* See Appendix B for definition.

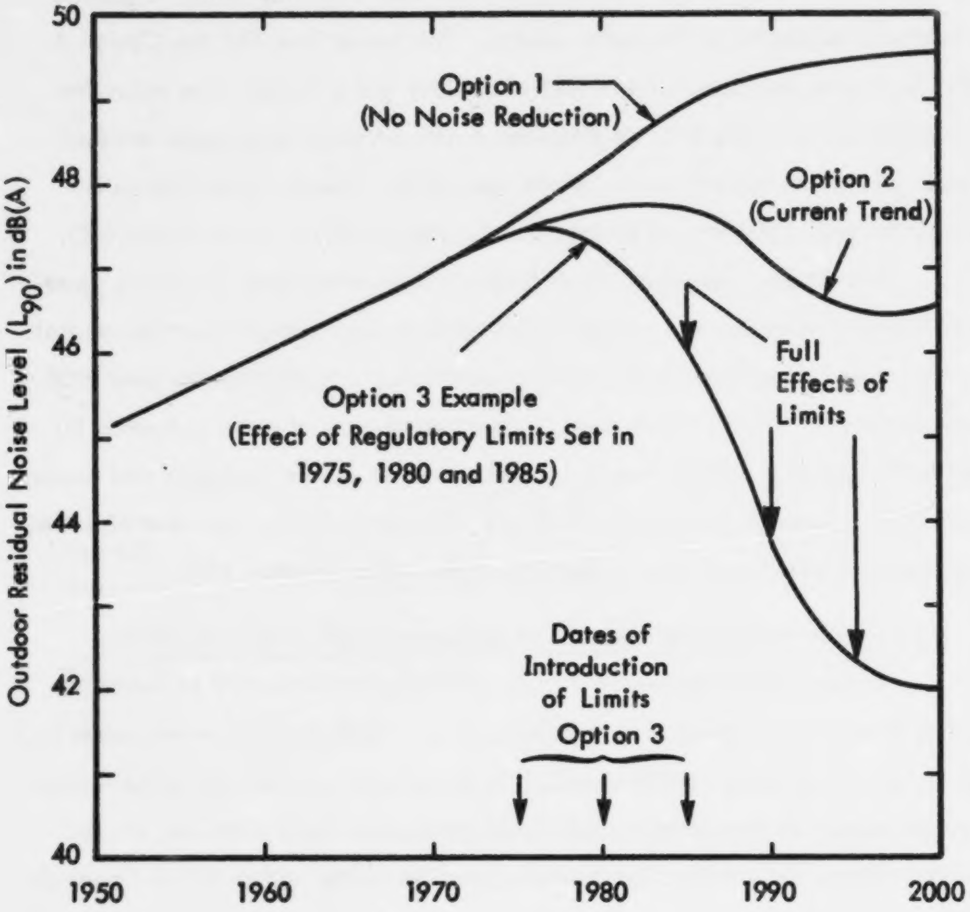

Figure 4-1. Estimated Long-Term Trend in Outdoor Residual Noise Levels in a Typical Residential Urban Community

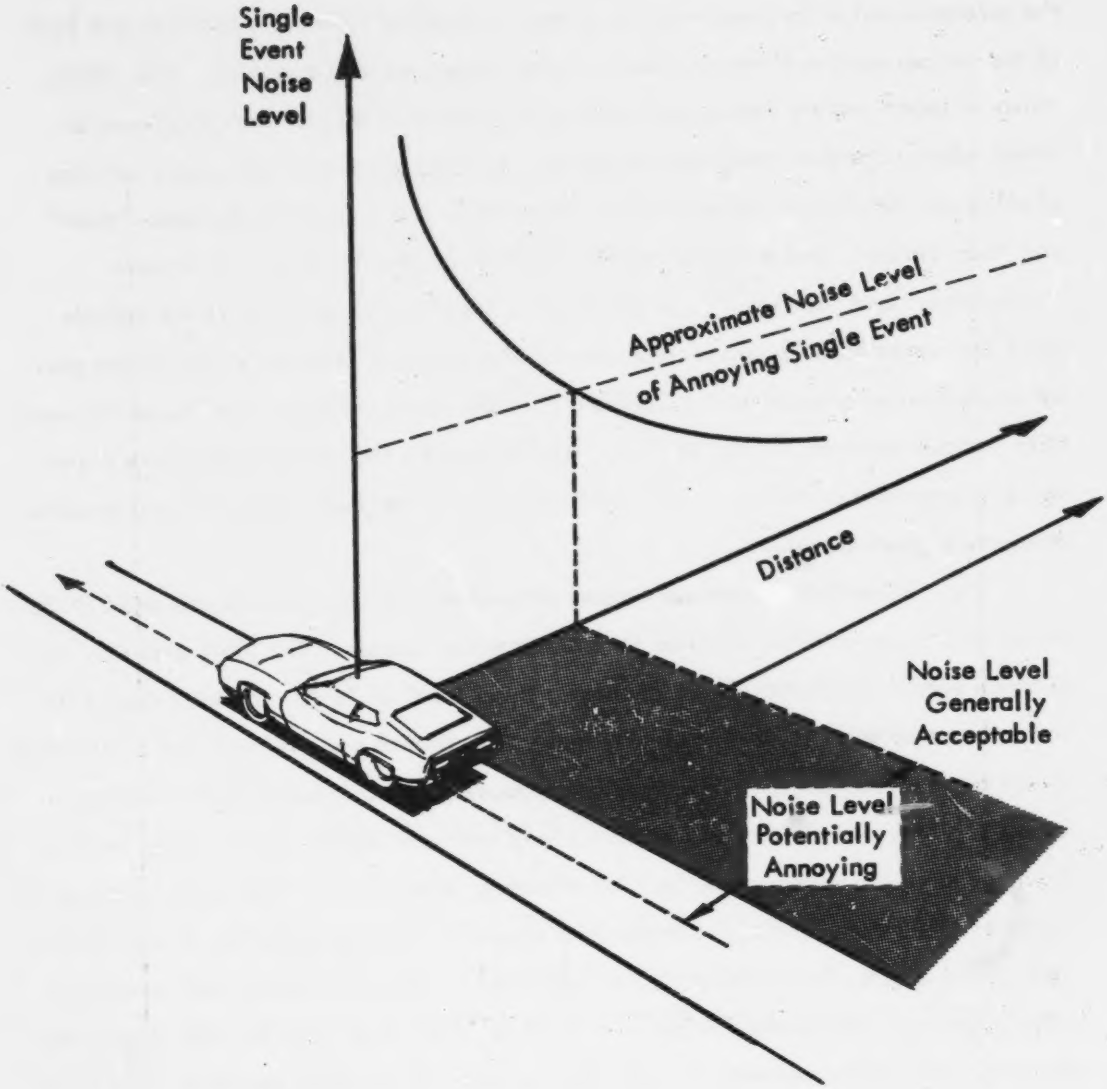
Single Event Noise Level
Approximate Noise Level of Annoying Single Event
Distance
Noise Level Generally Acceptable
Noise Level Potentially Annoying

Figure 4-2. Decay of Noise Level with Distance from Single Source Defines Relative Bounds of Annoyance Zone

the reference value for comparing the distances required between a receiver and each of the various sources if the sources are to be judged equally annoying. This SENEL value is approximately that experienced at a distance of 50 feet from a residential street when a standard passenger car passes. In subjective tests with motor vehicles of all types, this SENEL value has been found to be a dividing line between "quiet" and "acceptable", and is approximately 10 dB below the dividing line between "acceptable" and "noisy".[2,3] In these tests, the effective duration of the vehicle noise was approximately one second, so that the maximum noise level during the pass-by was numerically equal to the SENEL. Thus the maximum noise level found "acceptable" ranged between 72 and 82 dB(A), which brackets the sound level of one's own voice as measured at the ear. This "self voice level" has been suggested as a possible annoyance reference level.[4]

Table 4-6 summarizes typical values for maximum noise levels and SENEL values at a representative distance for transportation sources. The table also lists the distance within which the SENEL exceeds a fixed level of 72 dB. Examination of the various categories in Table 4-6 clearly shows that aircraft are obviously the outstanding source of annoying sounds. However, heavy trucks, highway buses, trains and rapid transit vehicles, which normally operate along restricted traffic routes, will also be a distinct source of intrusion – potentially affecting more people. This noise intrusion of single events is more severe in communities where the residual noise level is inherently low. For example, in a rural or "quiet" suburban community located well away from major highways, the residual noise level is 10 to 15 dB lower than in urban areas, and the passby of a noisy sportscar at night may momentarily increase the noise level by as much as 40 dB. Similarly, during the nighttime near a major highway, noise intrusion from single trucks is readily apparent due to the lower density of automobile traffic.

Recreational vehicles operating on land are in a class by themselves. Their high noise levels, wide usage in both residential and recreational areas, and the rapid increase in their number have all contributed to the current concern regarding noise pollution from these devices. The growth pattern is particularly significant, as indicated in Figure 4-3, which also illustrates the growth pattern of other consumer devices operated by internal combustion engines.

Table 4-6

Comparison of Major Surface Transportation System Categories According to Typical Maximum Noise Levels, Single Event Noise Exposure Levels (SENEL), and the Distance Within Which the SENEL is Greater than 72 dB

Category	Typical Single Event Levels			Distance[2] for SENEL Less Than 72 dB Feet
	Distance Feet	A-Weighted Noise Levels[1] dB re: 20 μN/m^2	SENEL dB re: 20 μN/m^2 and 1 sec	
AIRCRAFT				
Commercial – 4-Engine Turbofan	1000	103	111	>8000
Commercial – 2-Engine Turbofan	1000	96	104	>8000
Helicopters	1000	77	87	>2000
General Aviation Aircraft	1000	83	96	>2000
HIGHWAY VEHICLES				
Medium and Heavy Duty Trucks	50	84 (88)	87	700
Motorcycles (Highway)	50	82 (88)	85	540
Utility and Maintenance Vehicles	50	82 (88)	85	540
Highway Buses	50	82 (86)	83	540
Sports Cars (etc.)	50	75 (86)	78	170
City and School Buses	50	73 (85)	78	120
Light Trucks and Pickups	50	72 (86)	75	100
Passenger Cars (Standard)	50	69 (84)	72	50
RAIL VEHICLES				
Freight and Passenger Trains	50	94	114	>2000
Existing Rapid Transit	50	86	96	480
Trolley Cars (Old)	50	80	83	260
Trolley Cars (New)	50	68	71	40
RECREATIONAL VEHICLES				
Off-Road Motorcycles	50	85	90	750
Snowmobiles	50	85	90	750
Inboard Motorboats	50	80	85	400
Outboard Motorboats	50	80	85	400

[1] Values inside parentheses are typical for maximum acceleration. All other values are normal cruising speeds. Variations of 5 dB can be expected.

[2] Without shielding loss.

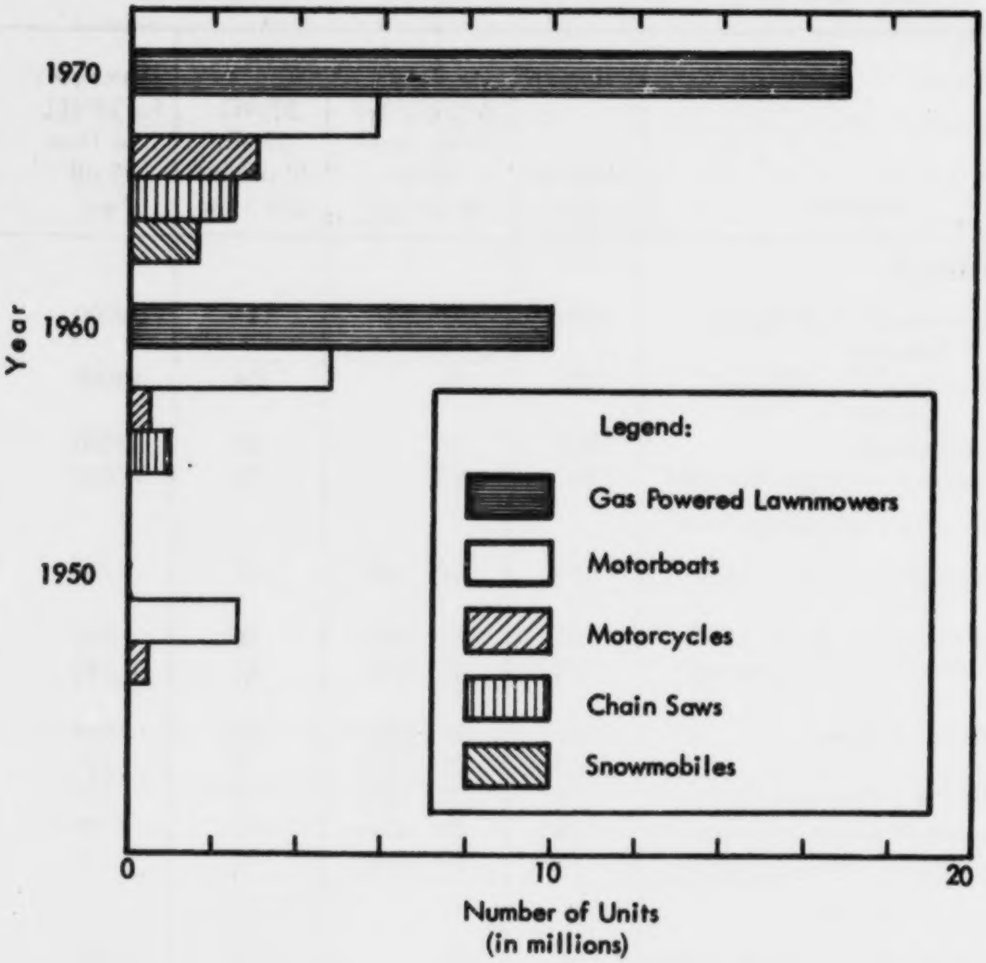

Figure 4-3. Approximate Growth of a Few Types of Noisy Recreational Vehicles and Outdoor Home Equipment. There were Negligibly Few Gas Powered Lawnmowers, Chain Saws and Snowmobiles in 1950

The noise intrusion of water craft is generally regarded to be fairly low, particularly since power boats are legally required to be at least 100 feet from shore when operating at high speed, thus minimizing their impact in local communities.

Looking ahead, the potential change in annoyance or intrusiveness of single events from surface transportation vehicles can be roughly evaluated by applying the potential noise reductions listed earlier in Table 4-1. This noise reduction also can be translated into a reduction of the spatial extent of potentially annoying single event levels by applying the following approximate corrections to the fourth column of Table 4-6.

Noise Reduction (From Table 4-1)	Correction Factor for SENEL Distance (Table 4-6)
0 dB	1
2	0.7
4	0.5
6	0.4
8	0.3
10	0.2

Applying the full potential noise reduction limits suggested in Table 4-1 for 1985, a substantial decrease in the annoyance would be achieved for most of the transportation categories. For example, with the exception of motorcycles and maintenance trucks, the vehicles commonly operating on urban streets would tend to have SENEL values less than 72 dB at 50 feet — a typical distance between a street and a residence.

4.4 Overall Assessment of Noise Impact by the Transportation System on Non-Participants

As suggested above, the cumulative effect of the repeated occurrence of intruding noises will place a different emphasis on individual transportation system categories than is obtained by considering only a single event. The land area within a Community Noise Equivalent Level (CNEL) of 65, as defined in Reference 2, is utilized to obtain a minimum estimate of the integrated noise impact for major urban highway systems and airport operations – the most important elements of the transportation system with respect to noise impacted areas. The general method for estimating noise impact contours around airports has been briefly described in Section 2.1. A summary of the method for estimating noise impact contours near highways is presented in Appendix B.

The noise impacted land within a Noise Exposure Forecast (NEF) 30 contour for airport operations throughout the nation in 1970 was 1450 square miles.[5] This NEF value is essentially equivalent to a CNEL of 65.[2] Therefore, for comparison, a CNEL of 65 was chosen as the outer boundary of noise impacted land near major urban highways. Calculations of the area enclosed between an effective "right of way" boundary and the CNEL 65 boundary for freeways, major arterials and collector streets gave a total impacted area of 540 square miles. This area was associated with freeways only, since the distance to the CNEL 65 boundary for the other types of roads was less than their effective right of way distance. Thus, the estimated noise impacted land within a CNEL 65 boundary for the two major transportation systems as of 1970 was approximately:

Highways	~ 545 square miles
Airports	~1450 square miles
Total	~1995 square miles

It should be emphasized that both of these estimates include land area which has compatible land use, as well as land area which does not. If it is assumed that the land use is similar to the average urban use, then the population density in 1970 would be approximately 5 thousand people per square mile. Thus, approximately 10 million people could be living in the noise impacted areas defined by this criterion. However, the expected reaction of a residential urban community to a noise intrusion which produced a CNEL of 65 would be "widespread complaints."[2] Therefore, this choice of a criterion for the contour boundary is conservative and the total impact for both commercial airports and freeways is certainly greater.

Furthermore, the criterion value for widespread complaints is a function of the residual noise level in the community. Consequently, a more accurate figure of noise impact would require assessing the number of people actually living within the CNEL 65 boundary in urban residential areas, plus the number of people within the CNEL 60 boundaries in normal suburban areas and the number within the CNEL 55 boundary in quiet suburban and rural areas. These lower CNEL boundary values account for the lower values expected for the residual noise levels in the quieter areas – thus allowing for an equal amount of relative noise intrusion for each type of residential community, as discussed in Reference 2. Accounting for the factors, it is conservative to estimate that at least 10 to 20 million individuals are impacted by these two types of noise intrusion.

The noise impacted land near rapid transit lines was not included in this analysis as there are only 386 miles of electric railway lines compared to about 9200 miles of urban freeways. This fact, combined with the effect of intermittent operation along rapid transit lines compared to the steady noise levels along freeways, indicates noise impacted land for the former will be much less.

Because helicopter flight route patterns are essentially random at present, it is practically impossible to define their noise impact in terms of land area or population. A sustained public reaction has not materialized, despite the intrusive nature of the sound, probably because of the irregularity of this usage pattern. However, widespread complaints have arisen due to air taxi services in New York and police operations in Los Angeles.

The airport noise impact due to general aviation aircraft operations is quite small when compared to the impact of commercial jet aircraft operations. This is due primarily to the lower noise levels for general aviation aircraft and to the fact that most of the airports are located in outlying sparsely populated areas, or the airports are sufficiently large that NEF 30 contours do not enclose significant residential areas. However, at some general aviation airports that have a high rate of operations for executive jets, a significant amount of residential land may be impacted by their noise. The amount of land area involved is not known.

To indicate past and future trends, the total impacted land area near freeways and airports has been estimated from 1955 to the year 2000. The resulting values, given in Table 4-7 represent the incompatible land area lying within a Community Noise Equivalent Level (CNEL) of 65. Future projections of noise impacted land have considered the effect of implementing the noise reduction options discussed at the beginning of this chapter. Thus, estimates of noise impacted land areas are given for 1985 and the year 2000 for both Option 2 (values in parentheses) and Option 3 examples. A marked reduction in impact is achieved by the latter. For Option 3, the estimated noise impacted land near airports is reduced by 88 percent from the 1970 value of 1995 square miles to 240 square miles. Based on a CNEL 65 boundary, noise impacted land near freeways is reduced to zero by the year 2000 on the assumption of a net noise reduction by vehicles and freeway noise barriers of about 5 dB beyond today's values.

These changes in land area, based on very conservative criteria for the noise impact boundary, correspond to an increase from a minimum of about 10 million people impacted today to about 17 million by the year 2000 assuming no further regulatory action (Option 2). Alternately, the estimated number of people impacted (based on this criterion) could be reduced by the year 2000 to no more than 1.2 million with a positive regulatory program to achieve further noise reduction for aircraft, highway vehicles and freeways. It is particularly important to note that the effect of imposing the noise limits on aircraft by FAR-36 is already showing at least a "holding action" on noise impact around airports. However, without any similar policy for highway vehicles at the national level, the potential growth in noise impact near freeways is severe.

These results must be viewed with extreme caution. First, they are based on a widespread complaint boundary which may or may not be deemed publicly acceptable. Second, they do not count the additional impacted area in communities with lower residual noise levels. Third, they do not account for the effect of lowering the future residual noise levels. For example, the 5 dB reduction of average residual

Table 4-7

Summary of Estimated Noise Impacted Land (Within CNEL 65 Contour) Near Airports and Freeways from 1955 to the Year 2000 with Future Estimates Based on Option 2 (Values in Parentheses) and Option 3 Examples

	Impacted Land Area – Square Miles		
	Near Airports	Near Freeways	Total
1955	~ 20	8	28
1960	200	75	275
1965	760	285	1045
1970	1450	545	1995
1985	780 (870)*	400 (1470)*	1180 (2340)*
2000	240 (1210)	0 (2050)	240 (3260)

*Number in parentheses is the estimated impact area if no further regulatory action is taken (Option 2). It assumes FAR Part 36 remains in force for aircraft, no new limits established for highway vehicle noise, and no change in existing freeway design concepts to increase noise reduction. Numbers outside of parentheses assume FAR-36 minus 10 dB for aircraft and additional combined noise reduction for freeways and highway vehicles of 3 dB by 1985 and 5 dB by the year 2000.

noise level estimated for Option 3 (see Figure 4-1) would require a 5 dB reduction in the level of intruding noises just to maintain the status quo. In this instance, a CNEL 60 in the year 2000 would be equivalent in terms of predicted community reaction to a CNEL 65 today. On the other hand, the interpretation of the results does not account for the long term 30 year evolution of land use patterns which undoubtedly will occur. For example, one of the principal reasons why railroads are not generally considered a major community noise problem today, is that, for the most part, the land use around railroads has slowly evolved to compatible usage over the past 30 to 60 years. The extent to which this factor will offset the previous factors is unknown.

Estimates have been made of the relative cost-effectiveness of alternate methods for reducing noise impacted land. For airports, reduction of noise at the source (i.e., quieter engines) has been shown to be clearly more cost-effective than reducing impact by land acquisition.[5] Continued progress to reduce jet aircraft noise should remain a first priority for Federal action on noise pollution. For freeways, improvement of design to increase noise reduction with barriers is more cost-effective by about 2 to 1 over land acquisition. Vehicle noise reduction is probably least cost-effective for reducing freeway noise impact only, but it gives other benefits for the total urban population. Thus, a balanced approach for reducing noise impact for the highway transportation system should emphasize both vehicle noise reduction and improved freeway design.

4.5 Impact on Participant or Passengers in Transportation Systems

The two significant effects of noise for participants or passengers in transportation systems are (a) potential hearing damage from excessive noise exposure, and (b) interference with speech communication for passengers.

Potential Hearing Damage

The potential hazard with respect to hearing damage for all categories of the transportation system is summarized in Figure 4-4 in terms of an equivalent 8-hour exposure level. This equivalent level is determined from the actual passenger noise

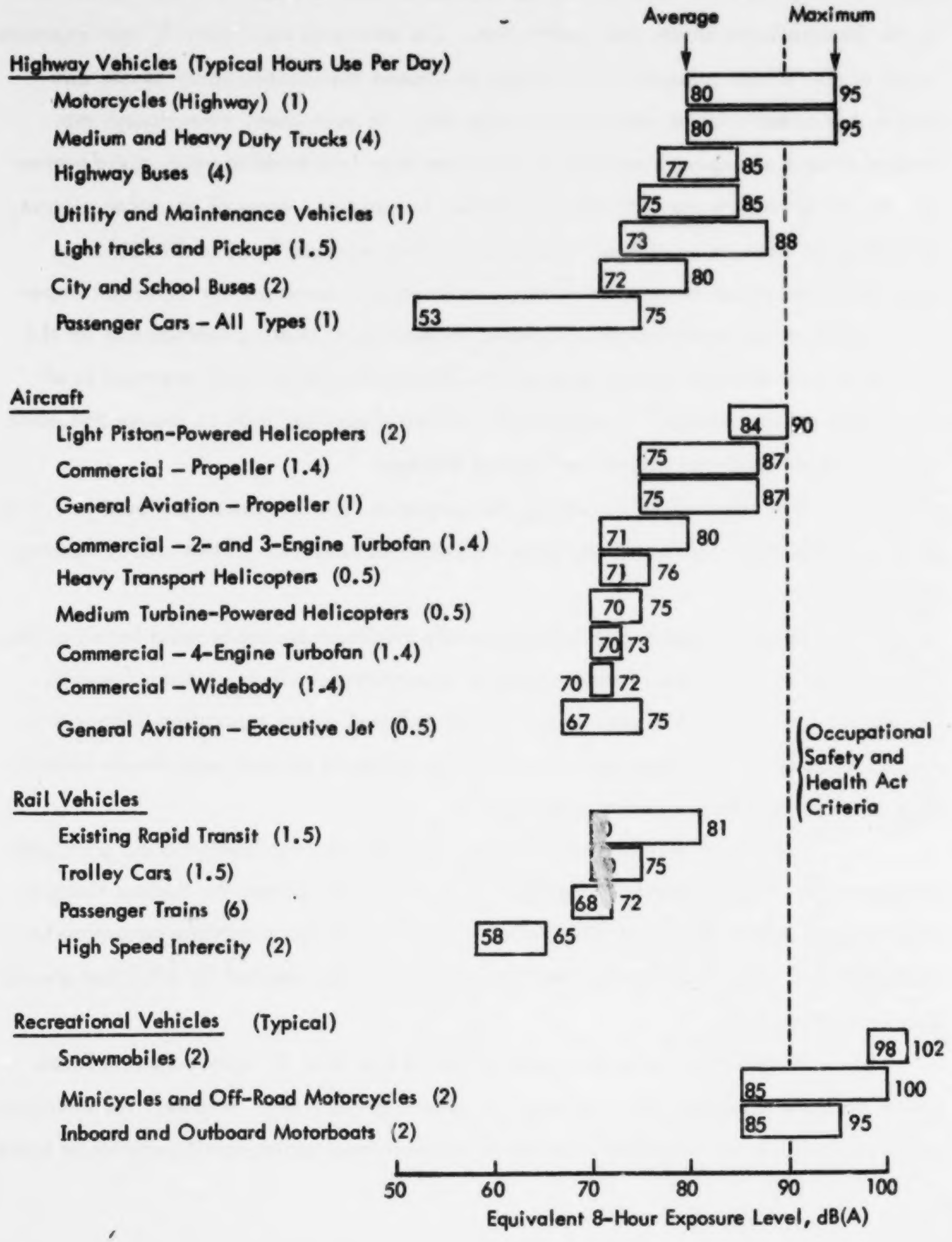

Figure 4-4. Potential Hearing Damage Contributions from Transportation System Categories in Terms of Equivalent 8-Hour Exposure Levels, for Passengers or Operators

exposure using the same rule for trading off time of exposure and level that is utilized in the Occupational Safety and Health Act. The estimated equivalent 8-hour exposure levels of five of the transportation categories exceed the Occupational Safety and Health Act criteria for an equivalent 8-hour day. In each case, even though the number of days of exposure per year is much less than in a working year, noise protection for the operator's ear is highly desirable. In addition, many of the other sources, including all those exceeding an equivalent 8-hour exposure level of 80 dB(A) are potentially hazardous to some indivuals, particularly in combination with their exposure to other noise environments. A proper evaluation of hearing damage risk for the individual must account for this cumulative effect of his entire daily exposure to all potentially harmful noises.[6] Consequently, efforts should be made to reduce this noise to minimize its potential hazard for hearing damage.

The effect of implementing the potential noise reduction outlined in Table 4-1 for transportation vehicles would be a substantial reduction of this risk of hearing damage.

Speech interference criteria specify maximum desirable noise levels at the listener's ear as a function of talker-listener separation for effective normal speech communication. Table 4-8 summarizes typical talker-listener separation distances in various transportation systems and corresponding maximum desired noise levels to minimize speech interference at these distances.

Comparing the last two columns, average internal levels for the principal passenger-carrying transportation categories generally fall within the desired limits to avoid speech interference. V/STOL rotary-wing aircraft are a notable exception for which internal noise levels are generally much higher than desired for effective speech communication.

It should be noted that a lower bound can exist for internal sound levels inside multiple passenger vehicles based on speech privacy requirements. While setting minimum levels is not necessarily desirable for short-haul rapid transit vehicles or buses used daily by commuters, long-haul passenger vehicles such as aircraft with close seat spacing are potential candidates for minimum levels based on speech privacy.

Table 4-8

Typical Passenger Separation Distances and Speech Interference Criteria Compared to Average Internal Noise Levels for Major Transportation Categories

	Talker-Listener Separation Feet	Speech Interference Limits* dB(A)	Average Internal Noise Levels dB(A)
Passenger Cars	1.6 to 2.8	73 to 79	78
Buses	1 to 1.7	79 to 85	82
Passenger Trains	1 to 1.7	79 to 85	68 to 70
Rapid Transit Cars	1 to 1.7	79 to 85	82
Aircraft (Fixed Wing)	1.1 to 1.7	79 to 84	82 to 83
V/STOL Aircraft	1.1 to 1.7	79 to 84	90 to 93

* Maximum noise levels to allow speech communication with expected voice level at specified talker-listener separation distances.[7]

A comparison of the average interior levels listed in Table 4-8 with speech privacy criteria shows that aircraft and rapid transit vehicles tend to meet this "minimum" level requirement for a typical seat pitch distance. However, internal levels for automobiles, buses and passenger trains generally fall below speech privacy criterion levels for typical seat-to-seat distances. Reduction of minimum levels required for speech privacy can be achieved only be increasing the seat spacing or increasing the barrier attenuation of sound between seats.

In summary, the impact of internal noise levels on current commercial passenger vehicles appears to be minimal, with the exception of V/STOL propeller or rotary-wing aircraft. For the latter, internal levels tend to be excessive according to both speech interference and potential hearing damage criteria. Noise levels for operators of heavy trucks, motorcycles and most gas engine-powered recreational vehicles are excessive and should be reduced to avoid potential hearing damage risks.

4.6 Environmental Impact for Internal Combustion Engine Devices

As indicated earlier in Figure 4-3, various labor-saving devices powered by internal combustion engines are a rapidly growing source of intrusive noise in many communities.

The principal characteristics of internal combustion engines as sources of potential noise impact are summarized in Table 4-9 using the same parameters presented earlier for transportation vehicles. In general, these devices are not significant contributors to average residual noise levels in urban areas. However, the relative annoyance of most of the garden care equipment tends to be high. This is due to the long duration of noise for these sources. This leads to a Single Event Noise Exposure Level much greater than the approximate annoyance threshold of 72 dB at a distance of 50 feet, a typical neighbor-to-neighbor distance. Clearly, further noise reduction for these devices is desirable. Similarly, a distinct local increase in the residual level in rural or wilderness areas may be experienced at distances up to one mile from such devices as chainsaws. As a result, they constitute a persistent source of annoyance for persons seeking the solitude of wilderness areas. In addition, use of chain saws can result in equivalent 8-hour exposure levels of 83 to 90 dB(A) for the operator, indicating the desirability of hearing protection for operators.

Potential Change in Noise Impact of Internal Combustion Engine Devices

The future growth in numbers of these devices is difficult to forecast accurately due to the lack of detailed data on their current usage. Such devices often have a short life span and, since they are seldom registered in any systematic way, the accuracy of future growth projections is questionable. The past growth of some of these devices has been spectacular, as shown in Figure 4-3. However, once the device has completed its basic market penetration, its growth rate should be expected to slow down to that of the general economy. Therefore, one can at least expect a general upward trend in their utilization as convenient and normally effective labor-saving

Table 4-9

Summary of Noise Impact Characteristics of Internal Combustion Engines

Source	A-Weighted(1) Noise Energy Kilowatt-Hrs Day	Typical A-Weighted Noise Level at 50 Feet dB(A)	Typical SENEL(4) at 50 Feet dB re 20μN/m² and 1 sec	8-Hr Exposure(2) Level dB(A)		Typical Exposure Time Hours
				Average	Maximum	
Lawn Mowers	63	74	111	74	82	1.5
Garden Tractors	63	78	N/A	N/A	N/A	N/A
Chain Saws	40	82	118	85	95	1
Snow Blowers	40	84	120	61	75	1
Lawn Edgers	16	78	111	67	75	1/2
Model Aircraft	12	78	108	70(3)	79(3)	1/4
Leaf Blowers	3.2	76	106	67	75	1/4
Generators	0.8	71	–	-	-	-
Tillers	0.4	70	106	72	80	1

(1) Based on estimates of the total number of units in operation per day.
(2) Equivalent level for evaluation of relative hearing damage risk.
(3) During engine trimming operation.
(4) See Appendix B for definition of SENEL.

devices which will always be in demand. This clearly represents an upward trend in their noise intrusion potential.

The combined effort by the public in demanding quieter products powered byinternal combustion engines and successful response to this demand by the manufacturers, should provide a substantial decrease in annoyance from this equipment. This reduction in annoyance of intruding noise from lawn mowers, chain saws, et cetera, will be the principal benefit of a broad noise reduction program for devices powered by internal combustion engines. The estimated potential noise reduction that might be expected in the future for some of these devices has been summarized earlier in Table 4-2. The noise reduction values were relative to current noise levels and were specified in terms of potential reductions that could be achieved by the 1975, 1980 and 1985 time periods (i.e., Option 3).

Full accomplishment of these noise reductions would largely eliminate annoyance problems in residential areas associated with use of lawn care equipment. However, the noise reduction potential for chain saws using existing technology is not sufficient to eliminate their annoyance problems or hearing damage risk for operators. Further noise reduction research is called for with these unique devices.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The data and discussions presented in this report have attempted to summarize many aspects of a very complex environmental problem. The manufacturing and transportation industries involved are a major segment of our national economy. Further, the transportation industry provides the essential service which enables the remainder of our economy to function. Unfortunately, noise is a byproduct of these industries. Thus, the majority of the sources discussed in this report contribute to noise pollution.

Highway vehicles are responsible for the outdoor residual noise level in our communities, as well as for freeway noise. Aircraft are responsible for the noise in the vicinity of airports. Recreation vehicles are responsible for disturbing noise in the remote wilderness areas, and lawn care equipment is responsible for excessive noise in the neighborhood. In addition, some of the sources in each of these general categories represent a potential hazard of hearing damage and most of the sources are often responsible for single-event noise intrusion in residential neighborhoods. Consequently, there are a variety of noise problems to be examined and solved within acceptable economic, technical and social constraints.

It will be a very difficult task to solve all of the major noise problems in the environment within these constraints. Such a task requires development of national noise goals, cause-and-effect noise system models, and economical and technical feasibility analyses which are beyond the scope of this report. However, the data presented in this report forms a necessary point of departure and suggests several useful directions for accomplishing the much needed task of controlling our noise environment for the benefit of our entire population.

This chapter presents the initial conclusions from this work, including the total impact on people of the noise sources discussed herein, industry's need for public guidance if it is to successfully implement noise reduction, and an identification of possible priorities for Federal action. It also contains a brief summary of major recommendations for the development of noise measurement standards, noise reduction demonstration projects, and research programs.

5.1 Noise Impact on People

The noise of each of the source categories in this report has been evaluated in Chapter 4, with reference to its potential impact. This evaluation, together with the analysis of the effect of noise in companion reports,[1,2] provides a basis for assessing the impact of the noise of the source categories on the population of this country. This assessment is made for (1) continuous outdoor noise sources which interfere with speech, (2) other noises resulting in community reaction and annoyance, and (3) noise which may be potentially hazardous to hearing.

Continuous Outdoor Noise which Interferes with Speech

The noise environment is primarily a product of man and his machine. It consists of an all-pervasive and non-specific residual noise, to which are added both constant and intermittent intrusive noises. The residual noise level in urban residential communities is generally the integrated result of the noise from traffic on streets and highways, principally automobiles and light trucks in the daytime, and including heavier trucks at night. The daytime outdoor residual noise levels vary widely with the type of community and can be grouped into the following approximate ranges:

• wilderness and rural	16 - 35 dB(A)
• suburban residential	36 - 45 dB(A)
• urban residential	46 - 55 dB(A)
• very noisy urban residential and downtown city	56 - 75 dB(A)

Residual noise levels in suburban and rural areas do not appear to interfere with speech communication at distances compatible with normal use of patios and backyards and often provides beneficial masking for speech privacy. However, some interference with outdoor speech is found in urban residential communities, and considerable continuous interference is found in the very noisy urban and downtown city areas. Thus, the use of outdoor space for conversation is effectively denied to an estimated 5 to 10 million people who reside in very noisy urban areas.

The backyards, patios and balconies facing an urban freeway are similarly rendered useless on a continuous basis, except when traffic is very light in the early morning hours. Although windows are kept closed in many dwelling units adjacent to freeways to keep out the noise, the level inside the dwelling may still be too high for relaxed conversation. An estimated 2.5 to 5 million people living near freeways are impacted significantly by this intrusive noise source. Probably another 7 to 14 million people are impacted to a lesser degree by the noise from traffic on the 96 thousand miles of major arterial roads in urban communities.

Thus, the combination of continuous daytime noise pollution caused by traffic on city streets, major arterials and freeways impairs the utility of the patios, porches and yards outside the dwelling units of approximately 7 to 14 percent of the total population. The analysis of Chapter 4 suggests that this situation will grow worse by the year 2000, unless the noise from automobiles and trucks is reduced. However, it could be improved by about 5 dB if noise reductions of 5 and 10 dB for automobiles and trucks, respectively, were accomplished by the 1985 time period. Such a reduction in the residual noise level should not destroy speech privacy in suburban areas and would improve the situation in the higher noise level urban areas. However, it would need to be supplemented by better land use planning and design of freeways and arterials to solve current and future noise problems.

Other Noises Resulting in Community Reaction and Annoyance

Adverse community reaction may be expected when the energy equivalent level of an intruding noise exceeds the residual noise level.[2] The degree of reaction depends primarily on the amount of the excess, and secondarily on additional factors such as season, personal attitude, and characteristics of the noise. For example, widespread complaints may generally be expected when the energy equivalent level exceeds the residual level by approximately 17 dB, and vigorous community action when the excess is approximately 33 dB. For these two values, the approximate percentage of the affected residents who are "very much annoyed" was found in one survey to be 37 and 87 percent, respectively. The impact of several forms of noise pollution, including intermittent noise from multiple single events such as aircraft overflights, infrequent diesel trucks on the highway, and the use of lawn care equipment, is often most effectively evaluated in terms of community reaction.

The most outstanding national problem which can be defined in these terms is the impact of aircraft noise. It is conservatively estimated that the number of people living in areas where aircraft noise exceeds the level required to generate widespread complaints is 7.5 million. This estimate assumes that all of the people affected live in residential urban communities. A more realistic estimate, including the people affected by aircraft noise who live in quiet and normal suburban communities, is 15 million. Most of the people impacted experience noise levels which interfere with speech, TV enjoyment, and indoor and outdoor speech communication every time an aircraft passes, and are often awakened or disturbed during sleep.

This has been a most difficult problem to solve because it grew to enormous proportions in only a few years, with no technically or economically feasible means available for its solution. Partial solutions of the noise problems of fixed-wing aircraft are now available. These solutions have resulted from Federal action to regulate noise and the incorporation of new noise reduction technology, which meets or exceeds the Federal standards, into new aircraft. However, an additional 10 dB of noise reduction over that achieved to date must be obtained through future technological research and development; otherwise, the problem cannot be solved for the remainder of this century without a massive alteration in land use near airports or the development of an entire new airport system well removed from urban areas. Realization of this additional noise reduction through technical advance and Federal regulation, together with effective procedures for implementing compatible land use planning should effect a solution through the year 2000.

In addition to the people impacted by aircraft noise, there are uncounted millions who are annoyed by sources such as: motorcycles, minicycles and sportscars operated in a noisy manner on residential streets; dunebuggies, chainsaws and snowmobiles operating in the wilderness; power lawnmowers, edge clippers and snowblowers operated by a neighbor on Sunday morning; and heavy trucks transporting freight at night. The single event noise exposure levels of almost every noise source category examined in this report can be classified as noisy when the source is operated in the urban residential environment. The principal exception is the automobile in its normal operation on a residential street, although automobiles, particularly sportscars and small imported compact cars, are judged noisy when operated with unnecessarily high acceleration.

The number of people who experience intermittent interference with speech and are otherwise annoyed by one or more of these sources at various times, probably include at least 75 percent of the population. However, the degree of lasting annoyance, and its accompanying probable community reaction, depends critically on the number of times the source operates per day, the time of day that it operates, people's attitude toward the source, and other factors.[2] There is no simple way of quantifying the magnitude of the overall impact in these terms since, unlike the airport or other industrial noise problems, there has been no centralized focal point for citizen expression. Therefore, perhaps the best indicator of the true community reaction is the significant increase of political activity by citizens operating through all levels of government to attempt to reduce the noise output of most of these sources through governmental regulation.

If the noise reductions selected in the Option 3 example of Chapter 4 were achieved by 1985, most of these noise sources would be expected to be judged acceptable when operated properly in the appropriate land use areas. However, considerable technical development is required to achieve this result with production hardware, and local operational and noise regulations will be required to ensure proper operation and restriction to appropriate land use areas.

Noise Which May be Potentially Hazardous with Respect to Hearing Damage

There is a long history of occupational noise environments which have resulted in hearing impairment of various degrees for some of the working population. For the most part, workers are now protected from such hazard through Federal enforcement of the provisions in the Occupational Health and Safety Act.

However, there are also many occasions where people may be exposed to potentially hazardous noise in a non-occupational environment. The more significant of these potential hazardous noise exposures for the sources in this report are summarized in Table 5-1. The equivalent 8-hour exposure level for these sources, on any day of use, was estimated in Chapter 4 to exceed 80 dB(A). Although the average person who is infrequently exposed to such noises will not necessarily suffer permanent hearing damage, frequent exposure to any one or several of these noises, or infrequent exposure in combination with industrial noise, will increase the risk of incurring permanent hearing impairment.

Table 5-1

Approximate Number of People (Operators and Passengers) in Non-Occupational Situations Exposed to Potentially* Hazardous Noise with Respect to Hearing Damage from Various Significant Sources

Source	Noise Level in dB(A)		Approximate Number of People In Millions
	Average**	Maximum	
Snowmobiles	108	112	1.60
Chain Saws	100	110	2.50
Motorcycles	95	110	3.00
Motorboats (over 45 HP)	95	105	8.80
Light Utility Helicopters	94	100	0.05
General Aviation Aircraft	90	103	0.30
Commercial Propeller Aircraft	88	100	5.00
Internal Combustion Lawnmowers and other Noisy Lawn Care Equipment	87	95	23.00
Trucks (Personal Use)	85	100	5.00
Highway Buses	82	90	2.00
Subways	80	93	2.15

*Although average use of any one of these devices by itself may not produce permanent hearing impairment, exposure to this noise in combination, or together with occupational noise will increase the risk of incurring permanent hearing impairment.

**Average refers to the average noise level for devices of various manufacture and model type.

Summary

These data show that approximately 22 to 44 million people have lost part of the utility of their dwellings and yards due to noise pollution from traffic and aircraft, and an even larger number of people are frequently subjected to intermittent speech interferences and annoyance from most of the sources considered in this report. Furthermore, some of these people, and others, are exposed to potentially hazardous noise, principally when operating or riding in noisy devices. Although the number exposed to potentially hazardous noise cannot be accurately assessed, since the people enumerated in Table 5-1 are not additive, a total of 30 million people might be a reasonable estimate.

Thus, noise pollution from these sources appears to impact at least 50 million people, or 25 percent of the population. Roughly one-half of this total impact is a potential health hazard, and the remaining one-half is an infringement on the ability to converse in the home environment. When the number of people who have occasional interference with speech as a result of intruding single event noise sources is included, the total number of people impacted probably rises to the order of 75 percent of the population. These percentages clearly show the need for action to reduce the number of devices which have potentially hazardous noise and are used by the public, and to reduce the outdoor noises which interfere with the quality of life.

5.2 Interaction Between Public and Industry

Much of the strength of the nation's economy, and the accompanying high standard of living, resulted from technical innovation and its utilization by industry in the development of new and better machines which fulfill people's needs. By-and-large, the performance criteria for these machines are defined in terms of the useful work which they will accomplish and the value of this work with respect to its cost. The success of any new product is determined in the market place, primarily in terms of the potential economic value of the product to the customer relative to its total cost, including both initial and operating costs.

In the case of acoustical devices such as musical instruments, hi-fi sets and speech communication equipment, sound characteristics are a primary performance criterion. However, for the other devices, noise is generally an unwanted byproduct which is not associated with the primary performance criteria. Only when a need for less noise is articulated, through customer preference or public action, does noise become one of the primary performance criteria. The information feedback process from the public to industry generally takes many years and often presents a conflicting set of needs. For example, the purchasers of devices such as motorcycles, sportscars, trucks and power lawnmowers often consider noise as a positive indicator of high performance. For the same reasons, the owners of many types of devices purposely operate them in their noisiest mode or modify them by removing their mufflers for "added power." In such cases, where the consumer and public interests diverge, industry responds to the consumer until the offended public articulates its requirements.

One of the best examples of the possible long term noise accommodation among industry, public and the market place is the standard American passenger car. In its sixty-year history, it has evolved from a noisy, sputtering, crude, low-powered vehicle to a relatively quiet, efficient, high-powered vehicle. Mufflers were installed before World War I to prevent scaring horses, and thus win a wider acceptance in the market place. In the 1920's, cities and towns set regulations requiring that all cars be muffled, primarily to ensure that owners retained the mufflers supplied with the vehicle in good working order. Without further action in the public sector, industry has made continuous progress toward quieting the automobile interior to gain wider acceptability in the market place, and in so doing has also attained reasonably acceptable exterior noise levels for individual automobiles.

Thus, although the market place provides industry with sufficient information to act in the national interest in the primary performance and cost aspects of its products, it does not necessarily provide such information about secondary performance factors such as noise. Consequently, unless the public articulates its requirements for noise, industry has little basis for establishing noise criteria and developing products which meet these criteria.

During the last few years, various governmental bodies have begun to express the public concern by developing and implementing noise regulations for various sources. With the exception of aircraft noise, where the Federal Government has begun to act, many of the remaining sources are being subjected to a series of separated, uncoordinated and often conflicting regulations. Actions by the public, as well as the data presented in this report, give clear evidence of the need for noise reduction. However, if industry is to make an effective response in controlling the noise of its products, it must have clear and consistent guidance. Only the Federal Govemment can fulfill this role.

5.3 Federal Action to Reduce Source Noise

Most of the sources discussed in this report have additional noise reduction potential which can be attained with application of today's technology. In many cases, these potential improvements will probably be sufficient to control noise pollution in the public interest. However, in some cases, including aircraft engines, tires and chainsaws, present technology is clearly insufficient to provide adequate noise control, and research is necessary. In either case, the eventual reduction of noise pollution in the nation requires establishment of a balanced set of noise goals which will enable priorities to be set for systematic exploitation of existing technology and development of new technology.

Together with these goals, source noise standards and the implementation of regulations must be promulgated to give industry a definite set of performance criteria for all of its products which are capable of causing noise pollution. Such standards should have time scales for achievement which are consistent with industrial design, prototype test and production cycles to encourage the most economical and effective incorporation of noise performance criteria into the total design of the product.

Regulations should cover at least all the sources which were shown in this report to be responsible for the significant noise pollution. High priority should be given to the sources which may constitute a potential hazard for hearing. This includes most of the recreational vehicles, internal combustion powered lawn care equipment and some transportation vehicles, as presented in Table 5-1. In addition, high priority should be given to all types of aircraft and large highway vehicles which are associated with the airport and freeway noise problems, and to the other elements of city traffic, so that the people living in major cities will eventually be able to enjoy relaxed conversation outdoors. Finally, high priority should be given to the lawn care equipment and recreational vehicles which cause unnecessary intrusion, intermittent interference with speech, and annoyance. Without an effective noise regulatory program, today's noise pollution problems will grow in size and impact an ever-increasing number of people.

5.4 Recommendations for Noise Reduction

Specific recommendations for programs to reduce the overall noise pollution of transportation systems and internal combustion engine devices are summarized in the following paragraphs. These recommendations are provided in four general groups in approximate descending order of priority within each group. The four types of programs and their basic objectives are:

- Demonstration Programs – Provide a clearly visible (or really audible) demonstration of the application of existing technology to noise reduction for a particular category. Economic practicality shall be considered but shall not be a firm constraint.

- Research Programs – Carry out applied or basic research to develop new technology required to define the ultimate noise reduction potential available beyond existing technology or achieve economically practical methods for utilizing existing technology, where adequate.

- Measurement Standards Programs – Develop, in conjunction with industry and professional organizations, effective procedures for noise certification of all categories of the transportation system not currently covered by Federal noise standards.

- Noise Certification Programs – Develop national standards for maximum noise levels of major transportation vehicles (similar conceptually to FAR Part 36) and internal combustion engine devices so that manufacturers can plan product development for noise control on a uniform basis. Control on usage relative to community noise abatement should be retained by local state, county and city governments.

Several criteria have been used to establish the approximate priority for the recommended programs. These criteria include:

- Action to reduce potential hearing damage risk to passengers or non-commercial operators of transportation vehicles or internal combustion engine devices.
- Action to reduce the noise impacted land area near airports and major urban highways.
- Action to reduce the annoyance from noise of increasing numbers of vehicles or ICE devices which generate higher noise levels.

Demonstration Programs

- Commercial Aircraft – Continue Federal commitments to the full range of aircraft noise reduction programs. Commercial jet aircraft are and will continue to be for the foreseeable future the major source of noise pollution in urban communities. Reduction of this noise impact will require vigorous pursuit by the Federal government, in conjunction with aircraft engine and airframe manufacturers of the currently planned demonstration programs. These include:
  - The "Quiet Engine" Program (NASA Lewis/General Electric)
  - Development of flightworthy nacelle retrofit packages (FAA/Boeing)

  - Prototype 150-passenger STOL aircraft to meet 95 EPNdB at 500 feet (NASA Program anticipated)
  - Small engine noise reduction program (WPAFB/AiResearch)

  Establish a program to demonstrate maximum noise reduction potential within the present state of the art for helicopters intended for law enforcement and other general governmental functions.

- General Aviation Aircraft – A major program should be formed at the Federal level to demonstrate the optimum state of the art in reducing propeller and engine noise for general aviation aircraft. The projected growth of the general aviation fleet over the next 20 years is sufficient to indicate that the growth in number and operation of urban general aviation airports will provide another source of significant noise impact for urban populations unless counteracting action is taken to minimize any increase in noise pollution corresponding to the growth in the general aviation fleet.

  Demonstration of very significant noise reductions for executive jet aircraft is now being made by some manufacturers. Further demonstration and implementation of this noise reduction should be fostered by strict enforcement of FAR Part 36 for all new or modified aircraft requiring a new flight certification.

- Highway Vehicles – Noise levels of new passenger cars are generally being limited by existing or proposed limits imposed by state law. No specific Federally-funded demonstration program is considered necessary at this time for such vehicles. However, tire noise presents a major obstacle to further substantial reduction of automobile noise and requires a separate high priority effort.

Noise levels for new trucks are also being partially limited by state laws. However, a demonstration program is recommended to foster industry competition to achieve substantial additional reduction in truck noise levels. Excluding tire noise, truck noise can be reduced substantially within the present state of the art. The principal objective of this demonstration program would be to define this state-of-the-art limit with due consideration given to economic practicality. The results of the program would provide a baseline for establishing research goals to improve the state of the art.

Noise levels for trucks generally increase with age. A demonstration program is recommended to define an optimum concept for truck overhaul which combines practical noise reduction concepts with optimum performance objectives to extend the economic life of the truck while minimizing its noise signature.

Sufficient demonstrations have been made of potential reduction in tire noise to indicate that an extensive research program is required to advance the state of the art.

A program to demonstrate practical noise reduction retrofit packages for existing utility and maintenance trucks (such as garbage trucks) would provide a basis for achieving compliance with desired reduction in annoyance from these vehicles.

- Recreation Vehicles – The motorcycle is the primary source of noise pollution from recreation vehicles. A program to demonstrate "quiet motorcycles" for both highway and off-highway use is recommended. This could take the form of an industry competition to achieve the maximum practical noise reduction within the present state of the art.

  An educational program for the potential user should be part of this effort to motivate the motorcyclist to employ a quiet muffler for all recreational uses.

Stringent reductions in noise from snowmobiles are imposed by state laws now in existence or proposed. It is felt that compliance with these regulations will effectively demonstrate noise reduction potential (within the current state of the art) for these vehicles.

A related program would provide a demonstration of an acceptable compromise between noise reduction and performance for high-powered pleasure boats used for ski-towing.

- Rapid Transit Vehicles – Substantial improvements have been made in reducing noise for several different rapid transit systems. However, there is a real need to bring together into one program, a demonstration of the best noise reduction features of all these systems – in other words, demonstrate the best noise reduction available with a rapid tranit system designed with noise reduction as a principal constraint.

- Internal Combustion Engine Devices – A demonstration program is recommended to achieve substantially lower noise levels for lawn mowers and chain saws. This might take the form of an industry competition and would have the objective of defining practical limits for noise reduction within the current state of the art, thus leading to research goals for improving this state of the art.

Research Programs

- Commercial Aircraft – Increased research on:
  - Fan/compressor noise
  - Core engine noise
  - Supersonic jet engine noise reduction
  - Advanced technology quiet aircraft
  - V/STOL propulsion systems.

- General Aviation Aircraft
  - Basic research on propeller noise should be pursued by propeller manufacturers.
  - Pursue improved concepts in engine muffler designs for reciprocating and turboshaft propeller aircraft.
  - Develop optimum lightweight methods for cabin noise treatment of general aviation aircraft.
  - Develop "quiet" turbofan engines specifically designed for mission requirements of executive jet aircraft.
- Highway Vehicles
  - Conduct a broad ranging research program on tire noise reduction. Objectives should include, but not be limited to, overcoming the current economic and safety constraints of quiet recap tires for the trucking industry.
  - Advanced technology research for quieting of truck noise with emphasis on overall system design tradeoff problems involving intake noise reduction versus engine block cooling concepts, engine casing enclosure techniques versus engine compartment cooling requirements, exhaust noise reduction versus exhaust pressure effects on engine performance.
  - Basic and applied research on noise reduction potential for new types of truck engines such as turboshaft drive, unique engine cycles (i.e., Wankel engine), or turbocharged two or four cycle diesel engines instead of roots-type blowers for diesels.
  - Basic and applied research on quieting of transit buses. Research objectives to emphasize reduction in wayside noise of engine intake experienced by bystanders as bus departs; and elimination of brake squeal.

- Applied research program to establish improved methods for evaluating noise levels generated by highway vehicle traffic. Study should include models for evaluating residual noise levels as well as noise impact areas near freeways as a function of freeway noise reduction design features.

- Recreation Vehicles
  - Wide ranging research program directed toward development of lightweight muffler designs adaptable to motorcycles, minicycles, snowmobiles, etc. Program should include full exploration of advanced materials and acoustics technology to achieve optimum performance with design constraints for these vehicles.
  - Applied research program to overcome systems problems in achieving additional noise reduction for gasoline-powered recreational vehicles. Approaches should reflect new technology or utilization of new techniques to reduce engine intake and engine casing noise on the assumption that the engine muffler program will be sufficiently successful so as to make these sources dominant.

- Rail Transit Vehicles and Ships
  - Conduct analysis of future noise impact from high speed above ground, ground surface and below ground rapid transit systems that may be developed over the next 15 to 25 years in major urban areas. Study to include evaluation of probable transportation demands and the noise impact generated by alternate methods for meeting this demand.
  - Conduct similar study for potential noise impact for high speed water transportation systems such as surface effect machines or hydrofoils that may be included in significant numbers in future urban transportation systems.

  - Depending on results of above programs, conduct advanced research on noise reduction techniques applicable to urban rapid transit systems for which a significant growth in noise impact is predicted.

- Devices Powered by Small Internal Combustion Engines
  - Adopt noise reduction research results or objectives for recreation vehicles to requirements for low-cost engine design constraints of lawn care and yard maintenance equipment. Particular attention to be paid to reducing noise of chain saws and lawn mowers with the use of advanced technology.

Measurement Standards and Noise Certification Limits

- Commercial Aviation
  - Continue utilization and periodic updating of FAR Part 36 for noise certification of commercial aircraft.
  - Establish comparable standards for STOL and VTOL aircraft.
- General Aviation Aircraft
  - Continue development of noise certification limits and measurement techniques for all categories of general aviation aircraft.
- Highway Vehicles
  - Update existing industry measurement standards for highway vehicles (such as the SAE method) to reflect more realistic operating conditions for the vehicle and measurement procedures more readily adaptable to local agency enforcement.
  - Develop standard techniques for noise measurement of individual components on trucks and cars to provide a uniform basis for noise control at the manufacturers level. Particular emphasis should be

placed on engine intake air and cooling components as well as tires. Specification of limits for these components should be the responsibility of manufacturers who must meet total system noise limits imposed by local or Federal government agencies.

  - Develop a noise measurement procedure and outline potential noise certification limits for vehicles at highway speeds (50 mph or greater) which fairly accounts for the influence of tire noise.

- Recreation Vehicles
  - Develop national standards for noise measurement techniques and minimum noise levels for all classes of recreation vehicles with emphasis on motorcycles.

- Devices Powered by Small Internal Combustion Engines
  - Standardize, at the national level, measurement techniques and noise certification limits for newly manufactured internal combustion engine devices such as lawn mowers and chain saws.
  - Establish minimum standards for noise certification of portable generators to be used for mobile homes.

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NOISE FROM TRANSPORTATION SYSTEMS, RECREATION VEHICLES AND DEVICES POWERED BY SMALL INTERNAL COMBUSTION ENGINES

APPENDICES

A MEASUREMENT STANDARDS
B METHODOLOGY FOR IMPACT ANALYSIS
C NOISE GENERATOR CHARACTERISTICS

APPENDIX A

MEASUREMENT STANDARDS

In this appendix, several typical measurement standards relevant to the categories of Transportation Systems and Devices Powered by Internal Combustion Engines are summarized. The purpose of this discussion is to provide insight into the procedures used to obtain the standard levels contained in the body of this report. However, it is not all-inclusive since an analysis of every standard applicable to these categories is beyond the scope of this appendix.

The purpose of a noise measurement standard is to establish a practical formal procedure for determining the noise output of a device under realistic and repeatable operating conditions.

In some instances, measurement standards may be created by civil agencies whereby they are set forth as a basis for verifying that the noise output of a device falls within specified legal limits. The FAR-36 specification for certification of jet aircraft contains such a measurement standard. The new-vehicle noise measurement procedure utilized by the California Highway Patrol is another example.

Voluntary measurement standards may also be created by manufacturers' associations, professional societies, or other member bodies of the American National Standards Institute. In these instances, the purpose of the standard is to establish a common measurement basis which may be utilized by manufacturers and users throughout the nation. It also serves as a guide to groups with a peripheral involvement in the product, such as subcontractors and distributors, as to the basis for measurement on the completed system. This type of standard is typified by the SAE standards for measurements on commercial vehicles, automobiles, and other types of internal combustion engine powered equipment. These voluntary measurement standards may frequently be incorporated into government regulations and ordinances which specify maximum noise levels for various devices. An example is SAE Standard J192 for snowmobiles, which is utilized by a number of states as the basis for legislation of maximum snowmobile noise. Although a number of the voluntary measurement standards have gained fairly wide acceptance in industry and government, they generally have not been developed for regulatory use. Therefore, the quantities measured and the operating procedures utilized may not be appropriate for regulation of noise at the source.

For example, the State of California adopted SAE Standard J986a as a noise test compliance method for automobiles. This approach has been criticized because it penalizes certain vehicles by rating them in a maximum noise-producing mode which, in a large percentage of cases, does not typify normal operation. As a result, luxury American automobiles with 400 to 500 cubic inch displacement engines have difficulty passing the full-throttle acceleration noise test, whereas small imports and sports cars have little difficulty. Yet in use, the luxury vehicle is generally considered acceptably quiet, whereas the smaller car often is not so judged. This inequity results from the fact that the luxury automobile normally operates at only a fraction of its potential power, whereas the small low-powered vehicle normally operates near maximum power. This situation exemplifies the case of a standard, designed to serve as a common measurement basis, being incorrectly applied to noise regulation.

The principal noise source categories analyzed in this report are summarized in Table A-1, with a listing of the major measurement standards which apply to these categories. As can be observed, a number of these categories are not covered by any specific measurement or regulatory standards.

Following Table A-1 are brief descriptions of the test methods incorporated in the standards and the recommended noise levels produced under these operating conditions. In addition, because of its significance as the first noise standard promulgated by the Federal Government, the FAR Part 36 Noise Standard for Aircraft Type Certification is presented in its entirety at the conclusion of this appendix. This certification standard demonstrates the detail and complexity required in some standards, and appropriate sections of it may serve as a model for future standards.

Table A-I

Summary of Major Noise Measurement Standards

Category	Applicable Noise Measurement Standard – Observer								
	None	FAR[1] Part 36	ISO[2] R362	CHP[3] Article 10	SAE[4] J331 Proposed	SAE J366	SAE J986a	SAE J192	SAE J952b
General Aviation Aircraft	X								
V/STOL	X								
Business Jets		X							
Subsonic Commercial Aircraft		X							
Trains	X								
Passenger Cars and Light Trucks GVW < 6000 pounds			X	X			X		
Trucks and Buses GVW > 6000 pounds			X	X		X			
Motorcylces			X	X	X				
Snowmobiles								X	
Pleasure Boats	X								
Other Devices Powered by I/C Engines, Lawn Mowers, etc.									X

[1] Federal Aviation Regulation.

[2] International Organization for Standardization.

[3] California Highway Patrol.

[4] Society of Automotive Engineers.

Title: FAR 36 – NOISE STANDARDS: AIRCRAFT TYPE CERTIFICATION
Issued November 3, 1969, last revision November 24, 1969

Originator: Federal Aviation Agency

Noise Source: Subsonic Transport and Turbojet Powered Aircraft

Purpose: FAR-36 is an FAA procedure for flight certification of all subsonic transport and turbojet aircraft. It establishes maximum allowable noise levels for new aircraft and a standardized procedure for their measurement.

Measurement Location: Landing – 1 nautical mile from threshold, directly under the aircraft path,

Takeoff – 3.5 nautical miles from brake release, directly under the aircraft path, and

Sideline – at the location of maximum noise along a line parallel to and at a distance of 0.35 nautical miles from the runway centerline, for aircraft which have four or more engines; and 0.25 nautical miles from the runway centerline, for aircraft which have three or fewer engines.

Procedure: Appropriate measurement instrumentation is set up at the specified locations. A series of takeoffs and landings are made by the aircraft to be certified, in accordance with prescribed engine power and flight profiles. This procedure is performed with the aircraft operating at maximum gross takeoff weight. Noise data taken during this procedure is subsequently analyzed for compliance with the specified limits.

Maximum Noise Limits: The noise limits of this regulation are set forth in terms of Effective Perceived Noise Levels and gross takeoff weight. For landing and sideline, these levels range from 102 EPNdB to 108 EPNdB. For takeoff, the levels range from 93 EPNdB to 108 EPNdB.

Other Requirements:	Additional specifications are set forth relating to the measurement instrumentation, weather conditions, flight profiles, test aircraft operating conditions, and the appropriate technique for calculating EPNdB.
Title:	ISO RECOMMENDATION R362 – MEASUREMENT OF NOISE EMITTED BY VEHICLES – First Edition, February, 1964.
Originator:	International Organization for Standardization
Noise Source:	Motor Vehicles
Purpose:	Establishes a procedure for measurement of the maximum exterior noise level for motor vehicles, consistent with normal driving conditions, and is capable of giving easily repeatable results.
Measurement Location:	Should consist of an extensive flat open space of some 50 meters radius, of which the central 20 meters would consist of concrete or asphalt paving.
Procedure:	Locate microphone 7.5 meters from the centerline of the vehicle path. Approach microphone in low gear range (generally second gear) at 50 kph, or 3/4 maximum rated engine rpm, or 3/4 maximum engine speed permitted by governor, whichever is lowest. At a point 10 meters ahead of microphone, accelerate fully and hold at full throttle until the vehicle is 10 meters beyond the microphone.
Recommended Maximum Level:	No recommendations made.

Title:	SAE J192 – EXTERIOR SOUND LEVEL FOR SNOWMOBILES Approved September 1970.
Originator:	Society of Automotive Engineers
Noise Source:	New Snowmobiles
Purpose:	Provides a procedure for measurement of maximum exterior sound level for snowmobiles.
Measurement Location:	Test site to be flat open space, free of large reflecting objects within 100 feet of either the vehicle or the microphone.
Procedure:	Locate microphone 50 feet from the centerline of the vehicle path. Vehicle operated on grass (3-inch height). Accelerate fully from standing start such that maximum rated engine rpm is achieved 25 feet ahead of the microphone. Hold this maximum rpm until 50 feet beyond microphone.
Recommended Maximum Level:	82 +2 dB(A) at 50 feet.

Title:	SAE J331 – PROPOSED – SOUND LEVELS FOR MOTORCYCLES Draft No. 5, April 30, 1971
Originator:	Society of Automotive Engineers
Noise Source:	Motorcycles
Purpose:	Establishes a procedure for determining maximum sound levels for all classes of motorcycles.
Measurement Location:	Test site shall be a flat open space, free of large reflecting objects within 100 feet of either the vehicle or the microphone.
Procedure:	Locate microphone 50 feet from the centerline of the vehicle path. Motorcycle usually operated in low gear. Approach

microphone at 2/3 maximum rated engine rpm. At a point of at least 25 feet ahead of microphone, accelerate fully to achieve maximum rate engine rpm at a point between 15 and 25 feet past the microphone.

Recommended Maximum Level: Recommended dB(A)* for motorcycles manufactured after January 1, 1972:

Engine Displacement	1972	1973	1974
170 cc and less	86	83	80
171 cc - 300 cc	90	87	84
More than 300 cc	92	89	86

*With an additional allowance of +2 dB

Title: SAE J366 – EXTERIOR SOUND LEVEL FOR HEAVY TRUCKS AND BUSES – Approved July 1969.

Originator: Society of Automotive Engineers

Noise Source: Trucks and Buses over 6000 pounds GVW

Purpose: Establishes the method for measuring the maximum exterior sound level for highway motor trucks, truck tractors and buses.

Measurement Location: Test site shall be flat open space, free of large reflecting objects within 100 feet of either the vehicle or the microphone.

Procedure: Locate microphone 50 feet from the centerline of the vehicle path. Approach microphone in a gear ratio selected such that at a point 50 feet ahead of the microphone, the vehicle is at no higher than 2/3 the maximum rated or governed engine speed. Accelerate fully such that maximum rated engine rpm is achieved between 10 and 100 feet beyond microphone and without exceeding 35 mph at end point.

Recommended Maximum Level: 88 +2 dB(A) at 50 feet.

Title: SAE J952b – SOUND LEVELS FOR ENGINE POWERED EQUIPMENT Approved May 1966, Last Revised January 1969.

Originator: Society of Automotive Engineers

Noise Source: Engine Powered Equipment

Purpose: Establishes procedure for measuring maximum sound levels for engine powered equipment.

Measurement Location: Test site shall consist of a flat open area, free of large reflecting objects within 100 feet of either the microphone or the test specimen.

Procedure: Locate microphone 50 feet from the test specimen. Operate equipment at the combination of load and speed which produces maximum sound level without violating the manufacturer's operating specification.

Recommended Maximum Levels:

	Type of Equipment	Maximum Sound Level dB(A) at 50 feet* (A-Weighting Network)
1.	Construction and industrial machinery	88
2.	Engine powered equipment of 5 hp or less intended for use in residential areas at frequent intervals	70
3.	Engine powered equipment exceeding 5 hp but not greater than 20 hp intended for use in residential areas at frequent intervals	78
4.	Engine powered commercial equipment of 20 hp or less intended for infrequent use in a residential area	88
5.	Farm and light industrial tractors	88

*An additional 2 dB allowance over the sound level limits is recommended to provide for variations in test site, vehicle operation, temperature gradients, wind velocity gradients, test equipment, and inherent differences in nominally identical vehicles.

Title: SAE J986a – SOUND LEVEL FOR PASSENGER CARS AND LIGHT TRUCKS – Approved July, 1967; Last Revised January, 1969

Originator: Society of Automotive Engineers

Noise Source: Passenger Cars and Light Trucks (of 6000 GVW or less)

Purpose: Provides a method for determining the maximum sound level for passenger cars and light trucks.

Measurement Location: Test area to be flat open space, free of large reflecting objects, within 100 feet of either the vehicle or the microphone.

Procedure: Locate microphone 50 feet from the centerline of the vehicle path. Approach microphone at 30 mph in a low gear range. At a point 25 feet ahead of microphone, accelerate at wide open throttle such that maximum rated rpm is achieved 25 feet beyond microphone.

Recommended Maximum Levels: 86 + 2 dB(A) at 50 feet.

Title:	CALIFORNIA ADMINISTRATIVE CODE, TITLE B, CHAPTER 2, SUBCHAPTER 4, ARTICLE 10, VEHICLE NOISE MEASUREMENT February 15, 1968.
Originator:	Department of California Highway Patrol
Noise Source:	All new motor vehicles offered for sale in the State of California. Three categories of motor vehicles are defined: (1) trucks and buses with gross weight greater than 6000 pounds; (2) trucks, buses, and passenger cars with gross weight under 6000 pounds; and (3) motorcycles.
Purpose:	Establishes procedures for implementation of Section 27160 of the California Vehicle Code which is concerned with limits on noise output of new motor vehicles offered for sale in the State of California.
Measurement Location:	Open area, free of reflecting surfaces within a 100-foot radius of the microphone and within 100 feet of the centerline of the path of the vehicle from the point where the throttle is opened to the point where the throttle is closed.
Operating Conditions:	Vehicles are operated along a path 50 feet distant from, and at right angles to, the measurement microphone. Category 1 (Truck and Buses $\geq$6000 pounds GVW): Operate vehicle under conditions of grade, load, acceleration, deacceleration and gear selection to achieve maximum noise at a speed of up to 35 mph. Category 2 (Light Truck, Passenger Cars; GVW $<$6000 pounds): Operate vehicle in a low gear range. Approach microphone at 30 mph, accelerate fully at a point 25 feet ahead of microphone and continue to 100 feet beyond microphone or a point at which maximum rated engine rpm is reached. Category 3 (Motorcycles): Motorcycle driven in second gear at constant speed corresponding to 60 percent of maximum rated engine rpm. Accelerate full at a point 25 feet ahead of microphone.

Noise Limits: New Vehicles offered for sale in California: *

	Manufactured Prior to January 1, 1973	Manufactured After January 1, 1973
Category 1	88 dB(A)	86 dB(A)
Category 2	86	84
Category 3	88	86

*per California Vehicle Code

Title: CALIFORNIA ADMINISTRATIVE CODE, TITLE 13, CHAPTER 2, SUBCHAPTER 4, ARTICLE 10, VEHICLE NOISE MEASUREMENTS, February 15, 1968.

Originator: Department of California Highway Patrol

Noise Source: Motor vehicles and combinations of vehicles subject to registration when operated on California highways.

Purpose: Establishes procedures for implementation of Section 23130 of the California Vehicle Code which is concerned with limits on noise output of motor vehicles operated on all California highways.

Measurement Location: Open area, free of large reflecting surfaces within a 100-foot radius of the microphone and within a 100-foot radius of the point on the centerline of the path of the vehicle nearest the microphone.

Operating Conditions: Sound level readings are recorded on vehicles which are in lanes of travel whose centerlines are at or beyond 50 feet from the microphone position.

Noise Limits*:	Speed Limit of 35 mph or less	Speed Limit of more than 35 mph
1. Motorcycles and motor vehicles of 6000 GVW or more		
(a) Before 1 January 1973	88 dB(A)	90 dB(A)
(b) After 1 January 1973	86	90
2. All other motor vehicles	82	86

* per California Vehicle Code

(with an additional allowance of + 2 dB)

PART 36—NOISE STANDARDS: AIRCRAFT TYPE CERTIFICATION

Subpart A—General

Sec.
36.1 Applicability.
36.2 Special retroactive requirements.
36.3 Compatibility with airworthiness requirements.
36.5 Limitation of part.

Subpart B—Noise Measurement and Evaluation

36.101 Noise measurement.
36.103 Noise evaluation.

Subpart C—Noise Limits

36.201 Noise limits.

Subpart D [Reserved]

Subpart E [Reserved]

Subpart F [Reserved]

Subpart G—Operating Information and Airplane Flight Manual

36.1501 Procedures and other information.
36.1581 Airplane Flight Manual.
Appendix A—Aircraft noise measurement under § 36.101
Appendix B—Aircraft noise evaluation under § 36.103
Appendix C—Noise levels for subsonic transport category and turbojet powered airplanes under § 36.201

AUTHORITY: The provisions of this Part 36 issued under secs. 313(a), 601, 603, and 611 of the Federal Aviation Act of 1958; 49 U.S.C. 1354, 1421, 1423, and 1431 and sec. 6(c) of the Department of Transportation Act; 49 U.S.C. 1655(c).

Subpart A—General

§ 36.1 Applicability.

(a) This part prescribes noise standards for the issue of type certificates, and changes to those certificates, for subsonic transport category airplanes, and for subsonic turbojet powered airplanes regardless of category.

(b) Each person who applies under Part 21 of this chapter for a type certificate must show compliance with the applicable requirements of this part, in addition to the applicable airworthiness requirements of this chapter.

(c) Each person who applies under Part 21 of this chapter for approval of an acoustical change described in § 21.93 (b) of this chapter must show that the airplane meets the following requirements in addition to the applicable airworthiness requirements of this chapter:

(1) The noise limits prescribed in Appendix C of this part, for airplanes that can achieve those noise levels, or lower noise levels, prior to the change in type design.

(2) The noise levels created by the airplane prior to the change in type design, measured and evaluated as prescribed in Appendixes A and B of this part, for airplanes that cannot achieve the noise limits prescribed in Appendix C of this part prior to the change in type design.

§ 36.2 Special retroactive requirements.

(a) Notwithstanding § 21.17 of this chapter, and irrespective of the date of application, each applicant covered by § 36.201 (b)(1) and (c)(1), and § C36.5 (c) of this part who applies for a new type certificate, must show compliance with the applicable provisions of this part.

(b) Notwithstanding § 21.101(a) of this chapter, each person who applies for an acoustical change to a type design specified in § 21.93(b) of this chapter must show compliance with the applicable provisions of this part.

§ 36.3 Compatibility with airworthiness requirements.

It must be shown that the airplane meets the airworthiness regulations constituting the type certification basis of the airplane under all conditions in which compliance with this part is shown, and that all procedures used in complying with this part, and all procedures and information for the flight crew developed under this part, are consistent witn the airworthiness regulations constituting the type certification basis of the airplane.

§ 36.5 Limitation of part.

Pursuant to 49 U.S.C. 1431(b)(4), the noise levels in this part have been determined to be as low as is economically reasonable, technologically practicable, and appropriate to the type of aircraft to which they apply. No determination is made, under this part, that these noise levels are or should be acceptable or unacceptable for operation at, into, or out of, any airport.

Subpart B—Noise Measurement and Evaluation

§ 36.101 Noise measurement.

The noise generated by the airplane must be measured under Appendix A of this part or under an approved equivalent procedure.

§ 36.103 Noise evaluation.

Noise measurement information obtained under § 36.101 must be evaluated under Appendix B of this part or under an approved equivalent procedure.

Subpart C—Noise Limits

§ 36.201 Noise limits.

(a) Compliance with this section must be shown with noise levels measured and evaluated as prescribed in Subpart B of this part, and demonstrated at the measuring points prescribed in Appendix C of this part.

(b) For airplanes that have turbojet engines with bypass ratios of 2 or more and for which—

(1) Application was made before January 1, 1967, it must be shown that the noise levels of the airplane are no greater than those prescribed in Appendix C of this part, or are reduced to the lowest levels that are economically reasonable, technologically practicable, and appropriate to the particular type design; and

(2) Application was or is made on or after January 1, 1967, it must be shown that the noise levels of the airplane are no greater than those prescribed in Appendix C of this part.

(c) For airplanes that do not have turbojet engines with bypass ratios of 2 or more and for which—

(1) Application was made before December 1, 1969, it must be shown that the lowest noise levels, reasonably obtainable through the use of procedures and information developed for the flight crew under § 36.1501 are determined; and

(2) Application was or is made on or after December 1, 1969, it must be shown that the noise levels of the airplane are no greater than those prescribed in Appendix C of this part.

(d) For aircraft to which paragraph (b)(1) of this section applies and that do not meet Appendix C of this part, a time period will be placed on the type certificate. The type certificate will specify that, upon the expiration of this time period, the type certificate will be subject to suspension or modification under section 611 of the Federal Aviation Act of 1958 (49 U.S.C. 1431) unless the type design of aircraft produced under that type certificate on and after the expiration date is modified to show compliance with Appendix C. With respect to any possible suspensions or modifications under this paragraph, the certificate holder shall have the same notice and appeal rights as are contained in section 609 of the Federal Aviation Act of 1958 (49 U.S.C. 1429).

Subpart G—Operating Information and Airplane Flight Manual

§ 36.1501 Procedures and other information.

All procedures, any other information for the flight crew, that are employed for obtaining the noise reductions prescribed in this part must be developed. This must include noise levels achieved during type certification.

§ 36.1581 Airplane flight manual.

(a) The approved portion of the Airplane Flight Manual must contain procedures and other information approved under § 36.1501. Except as provided in paragraph (b) of this section, no operating limitations may be furnished under this section. The following statement must be furnished near the listed noise levels:

> No determination has been made by the Federal Aviation Administration that the noise levels in this manual are or should be acceptable or unacceptable for operation at, into, or out of, any airport.

(b) If the weight used in meeting the takeoff or landing noise requirements of this part is less than the maximum weight or design landing weight, respectively, established under the applicable airworthiness requirements, those lesser weights must be furnished, as operating limitations, in the operating limitations section of the Airplane Flight Manual.

(Secs. 313(a), 601, 603, and 611 of the Federal Aviation Act of 1958, 49 U.S.C. 1354, 1421, 1423, and 1431, and sec. 6(c) of the Department of Transportation Act, 49 U.S.C. 1655(c))

Issued in Washington, D.C., on November 3, 1969.

J. H. SHAFFER,
Administrator.

APPENDIX A—AIRCRAFT NOISE MEASUREMENT UNDER § 36.101

Section A36.1 *Noise certification test and measurement conditions*—(a) *General.* This section prescribes the conditions under which noise type certification tests must be conducted and the measurement procedures that must be used to measure the noise made by the aircraft for which the test is conducted.

(b) *General test conditions.* (1) Tests to show compliance with established noise type certification levels must consist of a series of takeoffs and landings during which measurements must be taken at the measuring points defined in Appendix C of this part. The sideline noise measurements must also be made at symmetrical locations on each side of the runway. On each test takeoff, simultaneous measurements must be made at the sideline measuring points on both sides of the runway and also at the takeoff flyover measuring point. If the height of the ground at each measuring point differs from that of the nearest point on the runway by more than 20 feet, corrections must be made as defined in § A36.3(d) of this appendix.

(2) Locations for measuring noise from an aircraft in flight must be surrounded by relatively flat terrain having no excessive sound absorption characteristics such as might be caused by thick, matted, or tall grass, shrubs, or wooded areas. No obstructions which significantly influence the sound field from the aircraft may exist within a conical space above the measurement position, the cone being defined by an axis normal to the ground and by a half-angle 75° from this axis.

(3) The tests must be carried out under the following weather conditions:

(i) No rain or other precipitation.

(ii) Relative humidity not higher than 90 percent or lower than 30 percent.

(iii) Ambient temperature not above 86° F. and not below 41° F. at 10 meters above ground.

(iv) Airport reported wind not above 10 knots and crosswind component not above 5 knots at 10 meters above ground.

(v) No temperature inversion or anomalous wind conditions that would significantly affect the noise level of the aircraft when the noise is recorded at the measuring points defined in Appendix C of this part.

(c) *Aircraft testing procedures.* (1) The aircraft testing procedures and noise measurements must be conducted and processed in an approved manner to yield the noise evaluation measure designated as Effective Perceived Noise Level, EPNL, in units of EPNdB, as described in Appendix B of this part.

(2) The aircraft height and lateral position relative to the extended centerline of the runway must be determined by a method independent of normal flight instrumentation such as radar tracking, theodolite triangulation, or photographic scaling techniques to be approved by the FAA.

(3) The aircraft position along the flight path must be related to the noise recorded at the noise measurement locations by means of synchronizing signals. The position of the aircraft must be recorded relative to the runway from a point at least 4 nautical miles from threshold to touchdown during the approach and at least 6 nautical miles from the start of roll during the takeoff.

(4) The takeoff test may be conducted at a weight different from the maximum takeoff weight at which noise certification is requested if the necessary EPNL correction does not exceed 2 EPNdB. The approach test may be conducted at a weight different from the maximum landing weight at which noise certification is requested provided the necessary EPNL correction does not exceed 1 EPNdB. Approved data may be used to determine the variation of EPNL with weight for both takeoff and approach test conditions.

(5) The takeoff test must meet the conditions of § C36.7 of Appendix C of this part.

(6) The approach test must be conducted with the aircraft stabilized and following a 3°±0.5° approach angle and must meet the conditions of § C36.9.

(d) *Measurements.* (1) Position and performance data required to make the corrections referred to in § A36.3(c) of this appendix must be automatically recorded at an approved sampling rate. Measuring equipment must be approved by the FAA.

(2) Position and performance data must be corrected, by the methods outlined in § A36.3(d) of this appendix to standard pressure at sea level, an ambient temperature of 77° F., a relative humidity of 70 percent, and zero wind.

(3) Acoustic data must be corrected by the methods of § A36.3(d) of this appendix to standard pressure at sea level, an ambient temperature of 77° F., and a relative humidity of 70 percent. Acoustic data corrections must also be made for a minimum distance of 370 feet between the aircraft's approach path and the approach measuring point, a takeoff path vertically above the flyover measuring point and for differences of more than 20 feet in elevation of measuring locations relative to the elevation of the nearest point of the runway.

(4) The airport tower or another facility must be approved for use as the location at which measurements of atmospheric parameters are representative of those conditions existing over the geographical area in which aircraft noise measurements are made. However, the surfac wind velocity and temperature must be measured near the microphone at the approach, sideline, and takeoff measurement locations, and the tests are not acceptable unless the conditions conform to § A36.1(b)(3) of this appendix.

(5) Enough sideline measurement stations must be used during tests so that the maximum sideline noise is clearly defined with respect to location and level.

Section A36.2 *Measurement of aircraft noise received on the ground*—(a) *General.* (1) These measurements provide the data for determining one-third octave band noise produced by aircraft during testing procedures, at specific observation stations, as a function of time.

(2) Methods for determination of the distance form the observation stations to the aircraft include theodolite triangulation techniques, scaling aircraft dimensions on photographs made as the aircraft flies directly over the measurement points, radar altimeters, and radar tracking systems. The method used must be approved.

(3) Sound pressure level data for noise type certification purposes must be obtained with approved acoustical equipment and measurement practices.

(b) *Measurement system.* (1) The acoustical measurement system must consist of approved equipment equivalent to the following:

(i) A microphone system with frequency response compatible with measurement and analysis system accuracy as stated in paragraph (c) of this section.

(ii) Tripods or similar microphone mountings that minimize interference with the sound being measured.

(iii) Recording and reproducing equipment characteristics, frequency response, and dynamic range compatible with the response and accuracy requirements of paragraph (c) of this section.

(iv) Acoustic calibrators using sine wave or broadband noise of known sound pressure level. If broadband noise is used, the signal must be described in terms of its average and maximum rms value for a nonoverload signal level.

(v) Analysis equipment with the response and accuracy requirements of paragraph (d) of this section.

(c) *Sensing, recording, and reproducing equipment.* (1) The sound produced by the aircraft shall be recorded in such a way that the complete information, time history included, is retained. A magnetic tape recorder is acceptable.

(2) The characteristics of the system must comply with the recommendations given in International Electrotechnical Commission (IEC) Publication No. 179 with regard to the sections concerning microphone and amplifier characteristics. The text and specifications of IEC Publication No. 179 entitled: "Precision Sound Level Meters" are incorporated by reference into this part and are made a part hereof as provided in 5 U.S.C. 552(a)(1) and 1 CFR Part 20. This publication was published in 1965 by the Bureau Central de la Commission Electrotechnique Internationale located at 1, rue de Varembe, Geneva, Switzerland, and copies may be purchased at that place. Copies of this publication are available for examination at the DOT Library, Federal Office Building 10A Branch and at the Office of Noise Abatement both located at Headquarters, Federal Aviation Administration, 800 Independence Avenue, Washington, D.C. Moreover, copies of this publication are available for examination at the Regional Offices of the FAA. Furthermore, a historic, official file will be maintained by the Office of Noise Abatement and will contain any changes made to this publication.

(3) The response of the complete system to a sensibly plane progressive sinusoidal wave of constant amplitude must lie within the tolerance limits specified in IEC Publication No. 179, over the frequency range 45 to 11,200 Hz.

(4) If limitations of the dynamic range of the equipment make it necessary, high frequency preemphasis must be added to the recording channel with the converse deemphasis on playback. The preemphasis must be applied such that the instantaneous recorded sound pressure level of the noise signal between 800 and 11,200 Hz does not vary more than 20 dB between the maximum and minimum one-third octave bands.

(5) The equipment must be acoustically calibrated using facilities for acoustic free-field calibration and electronically calibrated as stated in paragraph (d) of this section.

(6) A windscreen must be employed with the microphone during all measurements of aircraft noise when the wind speed is in excess of 6 knots. Corrections for any insertion loss produced by the windscreen, as a function of frequency, must be applied to the measured data and the corrections applied must be reported.

(d) *Analysis equipment.* (1) A frequency analysis of the acoustical signal shall be performed using one-third octave filters complying with the recommendations given in International Electrotechnical Commission (IEC) Publication No. 225. The text and specifications of IEC publication No. 225 entitled "Octave, Half-Octave and Third-Octave Band Filters Intended for the Analysis of Sounds and Vibrations" are incorporated by reference into this part and are made a part hereof as provided in 5 U.S.C. 552(a)(1) and 1 CFR Part 20. This publication was published in 1966 by the Bureau Central de la Commission Electrotechnique Internationale located at 1, rue de Varembe, Geneva, Switzerland, and copies may be purchased at that place. Copies of this publication are available for examination at the Office of Noise Abatement and at the DOT Library, Federal Office Building 10A Branch both located at Headquarters, Federal Aviation Administration, 800 Independence Avenue, Washington, D.C. Moreover, copies of this publication are available for examination at the Regional Offices of the FAA. Furthermore a historic, official file will be maintained by the Office of Noise Abatement and will contain any changes made to this publication.

(2) A set of 24 consecutive one-third octave filters must be used. The first filter of the set must be centered at a geometric mean frequency of 50 Hz and the last of 10 kHz.

(3) The analyzer indicating device must be analog, digital, or a combination of both. The preferred sequence of signal processing is:

(i) Squaring the one-third octave filter outputs;

(ii) Averaging or integrating; and

(iii) Linear to logarithmic conversion.

The indicating device must have a minimum crest factor capacity of 3 and shall measure, within a tolerance of ±1.0dB, the true root-mean-square (rms) level of the signal in each of the 24 one-third octave bands. If other than a true rms device is utilized, it must be calibrated for nonsinusoidal signals and time varying levels. The calibration must provide means for converting the output levels to true rms values.

(4) The dynamic response of the analyzer to input signals of both full-scale and 20 dB less than full-scale amplitude, shall conform to the following two requirements:

(i) When a sinusoidal pulse of 0.5-second duration at the geometrical mean frequency of each one-third octave band is applied to the input, the maximum output value shall read 4 dB ± 1 dB less than the value obtained for a steady state sinusoidal signal of the same frequency and amplitude.

(ii) The maximum output value shall exceed the final steady state value by 0.5 ± 0.5 dB when a steady state sinusoidal signal at the geometrical mean frequency of each one-third octave band is suddenly applied to the analyzer input and held constant.

(5) A single value of the rms level must be provided every 0.5 ± 0.01 second for each of the 24 one-third octave bands. The levels from all of the 24 one-third octave bands must be obtained within a 50-millisecond period. No more than 5 milliseconds of data from any 0.5-second period may be excluded from the measurement.

(6) The amplitude resolution of the analyzer must be at least 0.25 dB.

(7) Each output level from the analyzer must be accurate within ±1.0 dB with respect to the input signal, after all systematic errors have been eliminated. The total systematic errors for each of the output levels must not exceed ±3 dB. For contiguous filter systems, the systematic correction between adjacent one-third octave channels may not exceed 4 dB.

(8) The dynamic range capability of the analyzer for display of a single aircraft noise event must be at least 55 dB in terms of the difference between full-scale output level and the maximum noise level of the analyzer equipment.

(9) The complete electronic system must be subjected to a frequency and amplitude electrical calibration by the use of sinusoidal or broadband signals at frequencies covering the range of 45 to 11,200 Hz, and of known amplitudes covering the range of signal levels furnished by the microphone. If broadband signals are used, they must be described in terms of their average and maximum rms values for a nonoverload signal level.

(e) *Noise measurement procedures.* (1) The microphones must be oriented so that the maximum sound received arrives as nearly as reasonable in the direction for which the microphones are calibrated. The microphones must be placed so that their sensing elements are approximately 4 feet above ground.

(2) Immediately prior to and after each test, a recorded acoustic calibration of the system must be made in the field with an acoustic calibrator for the two purposes of checking system sensitivity and providing an acoustic reference level for the analysis of the sound level data.

(3) For the purpose of minimizing equipment or operator error, field calibrations must be supplemented with the use of an insert voltage device to place a known signal at the input of the microphone, just prior to and after recording aircraft noise data.

(4) The ambient noise, including both acoustical background and electrical noise of the measurement system, must be recorded and determined in the test area with the system gain set at levels which will be used for aircraft noise measurements.

Section A36.3 *Reporting and correcting measured data*—(a) *General.* Data representing physical measurements or corrections to measured data must be recorded in permanent form and appended to the record except that corrections to measurements for normal equipment response deviations need not be reported. All other corrections must be approved. Estimates must be made of the individual errors inherent in each of the operations employed in obtaining the final data.

(b) *Data reporting.* (1) Measured and corrected sound pressure levels must be presented in one-third octave band levels obtained with equipment conforming to the standards described in § A36.2 of this appendix.

(2) The type of equipment used for measurement and analysis of all acoustic aircraft performance and meteorological data must be reported.

(3) The following atmospheric environmental data, measured at hourly intervals or less during the test period at the observation points prescribed in § A36.1(d)(4) of this appendix, must be reported:

(i) Air temperature in degrees Fahrenheit and relative humidity in percent.

(ii) Maximum, minimum, and average wind in knots and their direction.

(iii) Atmospheric pressure in inches of Mercury.

(4) Comments on local topography, ground cover, and events that might interfere with sound recordings must be reported.

(5) The following aircraft information must be reported:

(i) Type, model, and serial numbers (if any) of aircraft and engines.

(ii) Gross dimensions of aircraft and location of engines.

(iii) Aircraft gross weight for each test run.

(iv) Aircraft configuration such as flap and landing gear positions.

(v) Airspeed in knots.

(vi) Engine performance in pounds of net thrust, engine pressure ratios, jet exit temperatures, and fan or compressor shaft rev./min. as recorded by cockpit instruments and manufacturer's data.

(vii) Aircraft height in feet determined by a method independent of cockpit instrumentation such as radar tracking theodolite triangulation, or approved photographic techniques.

(6) Aircraft speed and position and engine performance parameters must be recorded at an approved sampling rate sufficient to correct to the noise type certification reference conditions prescribed in § A36.3(c) of this appendix. Lateral position relative to the extended centerline of the runway, configuration, and gross weight must be reported.

(c) *Noise type certification reference conditions*—(1) *Meteorological conditions.* Aircraft position and performance data and the noise measurements must be corrected to the following noise type certification reference atmospheric conditions:

(a) Sea level pressure of 2116 psf (76 cm mercury).

(b) Ambient temperature of 77° F. (ISA+10°C.).

(c) Relative humidity of 70 percent.

(d) Zero wind.

(2) *Aircraft conditions.* The reference condition for takeoff is the maximum weight except as provided in § 36.1581(b).

The reference conditions for approach are:

(a) Design landing weight, except as provided in § 36.1581(b).

(b) Approach angle of 3°.

(c) Aircraft height of 370 feet above noise measuring station.

(d) *Data corrections.* (1) The noise data must be corrected to the noise type certification reference conditions as stated in § A36.3(c) of this appendix. The measured atmospheric conditions must be those obtained in accordance with § A36.1(d)(4) of this appendix. Atmospheric attenuation of sound requirements are given in § A36.5 of this appendix.

(2) The measured flight path must be corrected by an amount equal to the difference between the applicant's predicted flight paths for the test conditions and for the noise type certification reference conditions. Necessary corrections relating to aircraft flight path or performance may be derived from approved data other than certification test data. The flight path correction procedure for approach noise must be made with reference to a fixed aircraft height of 370 feet and a glide angle of 3°. The effective perceived noise level correction must be less than 2 EPNdB to allow for:

(a) The aircraft not passing vertically above the measuring point.

(b) The difference between 370 feet and the actual minimum distance of the aircraft's ILS antenna from the approach measuring points.

(c) The difference between the actual approach angle and 3°.

Detailed correction requirements are given in § A36.6 of this appendix.

(3) If aircraft sound pressure levels do not exceed the background sound pressure levels by at least 10 dB in any one-third octave band, approved corrections for the contribution of background sound pressure levels to observed sound pressure levels must be applied.

(e) *Validity of results.* (1) The test results must produce three average EPNL values and their 90 percent confidence limits, each being the arithmetic average of the corrected acoustical measurements for all valid test runs at the takeoff, approach, and sideline measuring points, respectively. If more than one acoustic measurement system is used at any single measurement location (such as for the symmetrical sideline measuring points), the resulting data for each test run must be averaged as a single measurement.

(2) The minimum sample size acceptable for each of the three certification measuring points is six. The samples must be large enough to establish statistically for each of the three average noise type certification levels a 90 percent confidence limit not exceeding ±1.5 EPNdB. No test result may be omitted from the average process unless otherwise specified by the FAA.

(3) The average EPNL values and their 90 percent confidence limits obtained by the foregoing process must be those by which the noise performance of the aircraft is assessed against the noise type certification criteria, and must be reported.

Section A36.4 *Symbols and units*—(a) *General.* The symbols used in Appendixes A and B of this part have the following meanings.

Symbol	Unit	Meaning
ant		*Antilogarithm to the Base 10.*
C(k)	dB	*Tone Correction.* The factor to be added to PNL(k) to account for the presence of spectral irregularities such as tones at the k-th increment of time.
d	sec	*Duration Time.* The length of the significant noise time history being the time interval between the limits of t(1) and t(2) to the nearest second.
D	dB	*Duration Correction.* The factor to be added to PNLM to account for the duration of the noise.
EPNL	EPNdB	*Effective Perceived Noise Level.* The value of PNL adjusted for both the presence of discrete frequencies and the time history. (The unit EPNdB is used instead of the unit dB.)
f(i) or fi	Hz	*Frequency.* The geometrical mean frequency for the i-th one-third octave band.
F(i, k)	dB	*Delta-dB.* The difference between the original and background sound pressure levels in the i-th one-third octave band at the k-th interval of time.
h	dB	*dB-Down.* The level to be subtracted from PNLTM that defines the duration of the noise.
H	%	*Relative Humidity.* The ambient atmospheric relative humidity.
(i) or i		*Frequency Band Index.* The numerical indicator that denotes any one of the 24 one-third octave bands with geometrical mean frequencies from 50 to 10,000 Hz.
(k)		*Time Increment Index.* The numerical indicator that denotes the number of equal time increments that have elapsed from a reference zero.
log		*Logarithm to the Base 10.*
log n(a)		*Noy Discontinuity Coordinate.* The log n value of the intersection point of the straight lines representing the variation of SPL with log n.
M(b), M(c)		*Noy Inverse Slope.* The reciprocals of the slopes of the straight lines representing the variation of SPL with log n.
n	noy	*Perceived Noisiness.* The perceived noisiness at any instant of time that occurs in a specified frequency range.
n(i, k)	noy	*Perceived Noisiness.* The perceived noisiness at the k-th instant of time that occurs in the i-th one-third octave band.
n(k)	noy	*Maximum Perceived Noisiness.* The maximum value of all of the 24 values of n(i) that occurs at the k-th instant of time.
N(k)	noy	*Total Perceived Noisiness.* The total perceived noisiness at the k-th instant of time calculated from the 24-instantaneous values of n(i, k).
p(b), p(c)		*Noy Slope.* The slopes of the straight lines representing the variation of SPL with log n.
PNL	PNdB	*Perceived Noise Level.* The perceived noise level at any instant of time (the unit PNdB is used instead of the unit dB).
PNL(k)	PNdB	*Perceived Noise Level.* The perceived noise level calculated from the 24 values of SPL (i,k) at the k-th increment of time. (The unit PNdB is used instead of the unit dB.)
PNLM	PNdB	*Maximum Perceived Noise Level.* The maximum value of PNL(k) that occurs during the aircraft flyover. (The unit PNdB is used instead of the unit dB.)
PNLT	PNdB	*Tone Corrected Perceived Noise Level.* The value of PNL adjusted for the presence of spectral irregularities (discrete frequencies) at any instant of time. (The unit PNdB is used instead of the unit dB.)
PNLT(k)	PNdB	*Tone Corrected Perceived Noise Level.* The value of PNL(k) adjusted for the presence of discrete frequencies that occurs at the k-th increment of time. (The unit PNdB is used instead of the unit dB.)
PNLTM	PNdB	*Maximum Tone Corrected Perceived Noise Level.* The maximum value of PNLT(k) that occurs during the aircraft flyover. (The unit PNdB is used instead of the unit dB.)
s(i,k)	dB	*Slope of Sound Pressure Level.* The change in level between adjacent one-third octave band sound pressure levels at the i-th band for the k-th instant of time.
Δs(i, k)	dB	*Change in Slope of Sound Pressure Level.*
s'(i, k)	dB	*Adjusted Slope of Sound Pressure Level.* The change in level between adjacent adjusted one-third octave band sound pressure levels at the i-th band for the k-th instant of time.
$\bar{s}$(i, k)	dB	*Average Slope of Sound Pressure Level.*
SPL	dB re 0.0002 microbar.	*Sound Pressure Level.* The sound pressure level at any instant of time that occurs in a specified frequency range.
SPL(a)	dB re 0.0002 microbar.	*Noy Discontinuity Coordinate.* The SPL value of the intersection point of the straight lines representing the variation of SPL with log n.
SPL(b), SPL(c)	dB re 0.0002 microbar.	*Noy Intercept.* The intercepts on the SPL-axis of the straight lines representing the variation of SPL with log n.
SPL(i, k)	dB re 0.0002 microbar.	*Sound Pressure Level.* The sound pressure level at the k-th instant of time that occurs in the i-th one-third octave band.
SPL'(i, k)	dB re 0.0002 microbar.	*Adjusted Sound Pressure Level.* The first approximation to background level in the i-th one-third octave band for the k-th instant of time.
SPL''(i, k)	dB re 0.0002 microbar	*Background Sound Pressure Level.* The final approximation to background level in the i-th one-third octave band for the k-th instant of time.
SPLi	dB re 0.0002 microbar	*Maximum Sound Pressure Level.* The sound pressure level that occurs in the i-th one-third octave band of the spectrum for PNLTM.
SPLic	dB re 0.0002 microbar	*Corrected Maximum Sound Pressure Level.* The sound pressure level that occurs in the i-th one-third octave band of the spectrum for PNLTM corrected for atmospheric sound absorption.
t	sec	*Elapsed Time.* The length of time measured from a reference zero.
t(1), t(2)	sec	*Time Limit.* The beginning and end of the significant noise time history defined by h.
Δt	sec	*Time Increment.* The equal increments of time for which PNL(k) and PNLT(k) are calculated.
T	sec	*Normalizing Time Constant.* The length of time used as a reference in the integration method for computing duration corrections.
T	°F	*Temperature.* The ambient atmospheric temperature.
αi αi'	dB/feet. dB/1000 feet.	*Test Atmospheric Absorption.* The atmospheric attenuation of sound that occurs in the i-th one-third octave band for the measured atmospheric temperature and relative humidity.
αio αio'	dB/feet. dB/1000 feet.	*Reference Atmospheric Absorption.* The atmospheric attenuation of sound that occurs in the i-th one-third octave band for the reference atmospheric temperature and relative humidity.
β	degrees	*First Constant Climb Angle.*
γ	degrees	*Second Constant Climb Angle.*
δ ε	degrees. degrees.	*Thrust Cutback Angles.* The angles defining the points on the takeoff flight path at which thrust reduction is started and ended respectively.
η	degrees	*Approach Angle.*
Θ	degrees	*Takeoff Noise Angle.* The angle between the flight path and noise path for takeoff operation. It is identical for both measured and corrected flight paths.
λ	degrees	*Approach Noise Angle.* The angle between the flight path and the noise path for approach operation. It is identical for both measured and corrected flight paths.
Δ1	EPNdB	*PNLT Correction.* The correction to be added to the EPNL calculated from measured data to account for noise level changes due to differences in atmospheric absorption and noise path length between reference and test conditions.
Δ2	EPNdB	*Noise Path Duration Correction.* The correction to be added to the EPNL calculated from measured data to account for noise level changes due to the noise duration because of differences in flyover altitude between reference and test condition.
Δ3	EPNdB	*Weight Correction.* The correction to be added to the EPNL calculated from measured data to account for noise level changes due to differences between maximum and test aircraft weights.
Δ4	EPNdB	*Approach Angle Correction.* The correction to be added to the EPNL calculated from measured data to account for noise level changes due to differences between 3° and the test approach angle.
ΔAB Δβ Δγ Δδ Δε	feet. degrees. degrees. degrees. degrees.	*Takeoff Profile Changes.* The changes in the basic parameters defining the takeoff profile due to differences between reference and test conditions.

FLIGHT PROFILE IDENTIFICATION POSITIONS

Position	*Description*
A	Start of takeoff roll.
B	Liftoff.
C	Start of first constant climb.
D	Start of thrust reduction.
E	Start of second constant climb.
Ec	Start of second constant climb on corrected flight path.
F	End of noise certification takeoff flight path.
Fc	End of second constant climb on corrected flight path.
G	Start of noise certification approach flight path.
Gr	Start of noise certification approach on reference flight path.
H	Position on approach path directly above noise measuring station.
I	Start of level off.
Ir	Start of level off on reference approach flight path.
J	Touchdown.
K	Takeoff noise measuring station.
L	Sideline noise measuring station (not on flight track).

FLIGHT PROFILE IDENTIFICATION POSITIONS—Continued

Position	Description
M	End of noise type certification takeoff flight track.
N	Approach noise measuring station.
O	Threshold of approach end of runway
P	Start of noise type certification approach flight track.
Q	Position on measured takeoff flight path corresponding to PNLTM at station K.
Qc	Position on corrected takeoff flight path corresponding to PNLTM at station K.
R	Position on measured takeoff flight path nearest to station K.
Rc	Position on corrected takeoff flight path nearest to station K.
S	Position on measured approach flight path corresponding to PNLTM at station N.
Sr	Position on reference approach flight path corresponding to PNLTM at station N.
T	Position on measured approach flight path nearest to station N.
Tr	Position on reference approach flight path nearest to station N.
X	Position on measured takeoff flight path corresponding to PNLTM at station L.

FLIGHT PROFILE DISTANCES

Distance	Unit	Meaning
AB	feet	*Length of Takeoff Roll.* The distance along the runway between the start of takeoff roll and lift off.
AK	feet	*Takeoff Measurement Distance.* The distance from the start of roll to the takeoff noise measurement station along the extended centerline of the runway.
AM	feet	*Takeoff Flight Track Distance.* The distance from the start of roll to the takeoff flight track position along the extented centerline of the runway for which the position of the aircraft need no longer be recorded.
KQ	feet	*Measured Takeoff Noise Path.* The distance from station K to the measured aircraft position Q.
KQc	feet	*Corrected Takeoff Noise Path.* The distance from station K to the corrected aircraft position Qc.
KR	feet	*Measured Takeoff Minimum Distance.* The distance from station K to point R on the measured flight path.
KRc	feet	*Corrected Takeoff Minimum Distance.* The distance from station K to point Rc on the corrected flight path.
LX	feet	*Measured Sideline Noise Path.* The distance from station L to the measured aircraft position X.
NH	feet	*Aircraft Approach Height.* The vertical distance between the aircraft and the approach measuring station.
NS	feet	*Measured Approach Noise Path.* The distance from station N to the measured aircraft position S.
NSr	feet	*Reference Approach Noise Path.* The distance from station N to the reference aircraft position Sr.
NT	feet	*Measured Approach Minimum Distance.* The distance from station N to point T on the measured flight path.
NTr	feet	*Reference Approach Minimum Distance.* The distance from station N to point Tr on the corrected flight path; it equals 369 feet.
ON	feet	*Approach Measurement Distance.* The distance from the runway threshold to the approach measurement station along the extended centerline of the runway.

FLIGHT PROFILE DISTANCES—Continued

Symbol	Unit	Meaning
OP	feet	*Approach Flight Track Distance.* The distance from the runway threshold to the approach flight track position along the extended centerline of the runway for which the position of the aircraft need no longer be recorded.

Section A36.5 *Atmospheric attenuation of sound*—(a) *General.* The atmospheric attenuation of sound must be determined in accordance with the curves of Figure 15 presented in SAE ARP 866 or by the simplified procedure presented below. SAE ARP 866 is a publication entitled: "Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise" and the recommendations presented therein are incorporated by reference into this Part and are made a part hereof as provided in 5 U.S.C. 522(a)(1) and 1 CFR Part 20. This publication was published on August 31, 1964, by the Society of Automotive Engineers, Inc., located at 2 Pennsylvania Plaza, New York, N.Y. 10001, and copies may be purchased at that place. Copies of this publication are available for examination at the DOT Library, Federal Office Building 10A Branch and at the Office of Noise Abatement both located at Headquarters, Federal Aviation Administration, 800 Independence Avenue, Washington, D.C. Moreover, copies of this publication are available for examination at the Regional Offices of the FAA. Furthermore, a historic, official file will be maintained by the Office of Noise Abatement and will contain any changes made to this publication.

(b) *Reference conditions.* For the reference atmospheric conditions of temperature and relative humidity equal to 77° F. and 70 percent, respectively, and for all other conditions of temperature and relative humidity where their product is equal to or greater than 4,000, the sound absorption must be expressed by the following equation:

$$\alpha i o' = fi/500 \text{ (dB/1,000 ft.)}$$

$\alpha i o'$ is the atmospheric attenuation of sound that occurs in the i-th one-third octave band for the reference atmospheric conditions and fi is the geometrical mean frequency for the i-th one-third octave band.

(c) *Nonreference conditions.* (1) For all atmospheric conditions of temperature and relative humidity where their product is equal to or less than 4,000, the relationship between sound absorption, frequency, temperature, and humidity must be expressed by the following equation:

$$500\ \alpha i'/fi = (2/3)\ [(11/2) - (HT/1{,}000)]$$

$\alpha i'$ is the atmospheric attenuation of sound that occurs in the i-th one-third octave band for a relative humidity of H percent and a temperature of T° Fahrenheit.

(2) Figure A1 graphically illustrates the simplified relationship. The second equation represents the inclined line which is valid for all values of HT up to and including 4,000. For all values of 4,000 and greater, the horizontal line, represented by the first equation, is valid. The minimum, reference, and maximum values of humidity and temperature are indicated in Figure A1.

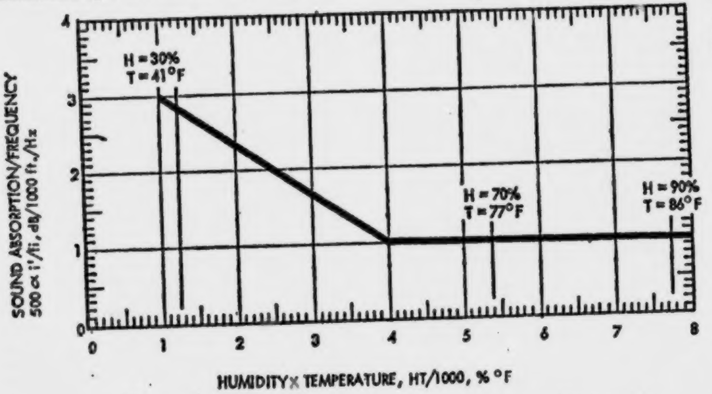


FIGURE A1. SIMPLIFIED RELATIONSHIP BETWEEN ATMOSPHERIC SOUND ATTENUATION, FREQUENCY, HUMIDITY, AND TEMPERATURE.

Section A36.6 *Detailed correction procedures*—(a) *General.* If the noise type certification test conditions are not equal to the noise certification reference conditions, appropriate positive corrections must be made to the EPNL calculated from the measured data. Differences between reference and test conditions which lead to positive corrections can result from the following:

(1) Atmospheric absorption of sound under test conditions greater than reference,

(2) Test flight path at higher altitude than reference, and

(3) Test weight less than maximum.

Negative corrections are permitted if the atmospheric absorption of sound under test conditions is less than reference and also if the test ~~flight path is at a lower~~ altitude than reference.

The takeoff test flight path can occur at a higher altitude than reference if the meteorological conditions permit superior aerodynamic performance ("cold day" effect). Conversely, the "hot day" effect can cause the takeoff test flight path to occur at a lower altitude than reference. The approach test flight path can occur at either higher or lower altitudes than reference irrespective of the meteorological conditions.

The correction procedures presented in the following discussion consist of one or more of five possible values added algebraically to the EPNL calculated as if the tests were conducted completely under the noise type certification reference conditions. The flight profiles must be determined for both takeoff and approach, and for both reference and test conditions. The test procedures require noise and flight path recordings with a synchronized time signal from which the test profile can be delineated, including the aircraft position for which PNLTM is observed at the noise measuring station. For takeoff, a flight profile corrected to reference conditions may be derived from manufacturer's data, and for approach, the reference profile is known.

The noise paths from the aircraft to the noise measuring station corresponding to PNLTM are determined for both the test and reference profiles. The SPL values in the spectrum of PNLTM are then corrected for the effects of:

(1) Change in atmospheric sound absorption,

(2) Atmospheric sound absorption on the change in noise path length,

(3) Inverse square law on the change in noise path length.

The corrected values of SPL are then converted to PNLT from which is subtracted PNLTM. The difference represents the correction to be added algebraically to the EPNL calculated from the measured data

The minimum distances from both the test and reference profiles to the noise measuring station are calculated and used to determine a noise duration correction due to the change in the altitude of aircraft flyover. The duration correction is added algebraically to the EPNL calculated from the measured data.

From approved data in the form of curves or tables giving the variation of EPNL with takeoff weight and also for landing weight, corrections are determined to be added to the EPNL calculated from the measured data to account for noise level changes due to differences between maximum and test aircraft weights.

From approved data in the form of curves or tables giving the variation of EPNL with approach angle, corrections are determined to be added algebraically to the EPNL calculated from measured data to account for noise level changes due to differences between 3° and the test approach angle.

(b) *Takeoff profiles*. Figure A2 illustrates a typical takeoff profile. The aircraft begins the takeoff roll at point A, lifts off at point B, and initiates the first constant climb at point C at an angle β. The noise abatement thrust cutback is started at point D and completed at point E where the second constant climb is defined by the angle γ (usually expressed in terms of the gradient in per cent).

The end of the noise type certification takeoff flight path is represented by aircraft position F whose vertical projection on the flight track (extended centerline of the runway) is point M. The position of the aircraft must be recorded for a distance AM of at least 6 nautical miles.

Position K is the takeoff noise measuring station whose distance AK is specified as 3.5 nautical miles. Position L is the sideline noise measuring station located on a line parallel to and a specified distance from the runway centerline where the noise level during takeoff is greatest.

The takeoff profile is defined by the following five parameters: AB, the length of takeoff roll; β, the first constant climb angle; γ, the second constant climb angle; and δ and ϵ, the thrust cutback angles. These five parameters are functions of the aircraft performance and weight and the atmospheric conditions of temperature, pressure, and wind velocity and direction. If the test conditions are not equal to the reference conditions, the corresponding test and reference profile parameters will be different as shown in Figure A3. The profile parameter changes, identified as ΔAB, $\Delta\beta$, $\Delta\alpha$, $\Delta\delta$, and $\Delta\epsilon$, can be derived from the manufacturer's data (approved by the FAA) and can be used to define the flight profile corrected to the reference conditions. The relationships between the measured and corrected takeoff flight profiles can then be used to determine the corrections, which if positive, must be applied to the EPNL calculated from the measured data.

NOTE: Under reference atmospheric conditions and with maximum takeoff weight, the gradient of the second constant climb angle, γ, is specified to be not less than 4 percent. However, the actual gradient will depend upon the test atmospheric conditions, assuming maximum takeoff weight and the parameters characterizing engine performance are constant (rpm, epr, or any other parameter used by the pilot).

Figure A4 illustrates portions of the measured and corrected takeoff flight paths including the significant geometrical relationships influencing sound propagation. EF represents the measured second constant flight path with climb angle γ, and EcFc represents the corrected second constant flight path at reduced altitude and with reduced climb angle $\gamma - \Delta\gamma$.

Position Q represents the aircraft location on the measured takeoff flight path for which PNLTM is observed at the noise measuring station K, and Qc is the corresponding position on the corrected flight path. The measured and corrected noise propagation paths are KQ and KQc, respectively, which form the same angle θ with their flight paths.

Position R represents the point on the measured takeoff flight path nearest the noise measuring station K, and Rc is the corresponding position on the corrected flight path. The minimum distance to the measured and corrected flight paths are indicated by the lines KR and KRc, respectively, which are normal to their flight paths.

(c) *Approach profiles*. Figure A5 illustrates a typical approach profile. The beginning of the noise type certification approach profile is represented by aircraft position G whose vertical projection on the flight track (extended centerline of the runway) is point P. The position of the aircraft must be recorded for a distance OP from the runway threshold O of at least 4 nautical miles.

The aircraft approaches at an angle η, passes vertically over the noise measuring station N at a height of NH, begins the level off at position I, and touches down at position J. The distance ON is specified as 1.0 nautical mile.

The approach profile is defined by the approach angle η and the height NH which are functions of the aircraft operating conditions controlled by the pilot. If the measured approach profile parameters are different from the corresponding reference approach parameters (3° and 370 feet, respectively, as shown in Figure A6), corrections, if positive, must be applied to the EPNL calculated from the measured data.

Figure A7 illustrates portions of the measured and reference approach flight paths including the significant geometrical relationships influencing sound propagation. GI represents the measured approach path with approach angle η, and GrIr represents the reference approach flight path at lower altitude and approach angle of 3°.

Position S represents the aircraft location on the measured approach flight path for which PNLTM is observed at the noise measuring station N, and Sr is the corresponding position on the reference approach flight path. The measured and corrected noise propagation paths are NS and NSr, respectively, which form the same angle λ with their flight paths.

Position T represents the point on the measured approach flight path nearest the noise measuring station N, and Tr is the corresponding point on the reference approach flight path. The minimum distances to the measured and reference flight paths are indicated by the lines NT and NTr, respectively, which are normal to their flight paths.

NOTE: The reference approach flight path is defined by $\eta = 3°$ and $NH = 370$ feet. Consequently, NTr can also be defined; $NTr = 369$ feet to the nearest foot and is, therefore, considered to be one of the reference parameters.

(d) *PNLT corrections*. Whenever the ambient atmospheric conditions of temperature and relative humidity differ from the reference conditions (77° F. and 70 percent, respectively) and whenever the measured takeoff and approach flight paths differ from the corrected and reference flight paths respectively, it may be necessary or desirable to apply corrections to the EPNL values calculated from the measured data. If the corrections are required, they must be calculated as described below.

Referring to the takeoff flight path shown in Figure A4, the spectrum of PLNTM observed at station K for the aircraft at position Q, is decomposed into its individual SPLi values. A set of corrected values are then computed as follows:

$$\begin{aligned} SPLic = SPLi &+ (\alpha i - \alpha io)\,KQ \\ &+ \alpha io\,(KQ - KQc) \\ &+ 20 \log\,(KQ/KQc) \end{aligned}$$

where SPLi and SPLic are the measured and corrected sound pressure levels, respectively, in the i-th one-third octave band. The first correction term accounts for the effects of change in atmospheric sound absorption where αi and αio are the sound absorption coefficients for the test and reference atmospheric conditions, respectively, for the i-th one-third octave band and KQ is the measured takeoff noise path. The second correction term accounts for the effects of atmospheric sound absorption on the change in the noise path length where KQc is the corrected takeoff noise path. The third correction term accounts for the effects of the inverse square law on the change in the noise path length.

The corrected values of SPLic are then converted to PNLT and a correction term calculated as follows:

$$\Delta 1 = PNLT - PNLTM$$

which represents the correction to be added algebraically to the EPNL calculated from the measured data.

The same procedure is used for the approach flight path except that the values for SPLic relate to the approach noise paths shown in Figure A7 as follows:

$$\begin{aligned} SPLic = SPLi &+ (\alpha i - \alpha io)\ NS \\ &+ \alpha io\ (NS - NSr) \\ &+ 20 \log (NS/NSr) \end{aligned}$$

where NS and NSr are the measured and reference approach noise paths, respectively. The remainder of the procedure is the same as for the takeoff flight path.

The same procedure is used for the sideline flight path except that the values for SPLic relate only to the measured sideline noise path as follows:

$$SPLic = SPLi + (\alpha i - \alpha io)\ LX$$

where LX is the measured sideline noise path from station L (Figure A2) to position X of the aircraft for which PNLTM is observed at station L. Only the correction term accounting for the effects of change in atmospheric sound absorption is considered. The difference between the measured and corrected noise path lengths are assumed negligible for the sideline flight path. The remainder of the procedure is the same as for the takeoff flight path.

(e) *Duration corrections.* Whenever the measured takeoff and approach flight paths differ from the corrected and reference flight paths, respectively, it may be necessary or desirable to apply duration corrections to the EPNL values calculated from the measured data. If the corrections are required, they shall be calculated as described below.

Referring to the takeoff flight path shown in Figure A4, a correction term is calculated as follows:

$$\Delta 2 = -10 \log (KR/KRc)$$

which represents the correction to be added algebraically to the EPNL calculated from the measured data. The lengths KR and KRc are the measured and corrected takeoff minimum distances, respectively, from the noise measuring station K to the measured and corrected flight paths. The negative sign indicates that, for the particular case of a duration correction, the EPNL calculated from the measured data is reduced if the measured flight path is at a greater altitude than the corrected flight path.

The same procedure is used for the approach flight path except that the correction relates to the approach minimum distances shown in Figure A7 as follows:

$$\Delta 2 = -10 \log (NT/369)$$

where NT is the measured approach minimum distance from the noise measuring station N to the measured flight path and 369 feet is the minimum distance from station N to the reference flight path.

No duration correction is computed for the sideline flight path because the differences between the measured and corrected flight paths are assumed negligible.

(f) *Weight corrections.* Whenever the aircraft weight, during either the noise type certification takeoff, sideline, or approach test, is less than the corresponding maximum takeoff or landing weight, a correction must be applied to the EPNL value calculated from the measured data. The corrections are determined from approved data in the form of tables or curves such as schematically indicated in Figures A8 and A9. The data must be applicable to the noise type certification reference atmospheric conditions.

(g) *Approach angle corrections.* Whenever the aircraft approach angle during the noise type certification approach test is greater than 3°, a correction must be applied to the EPNL value calculated from the measured data. The corrections are determined from approved data in the form of tables or curves such as schematically indicated in Figure A10. The data must be applicable to the noise type certification reference atmospheric conditions and to the test landing weight.

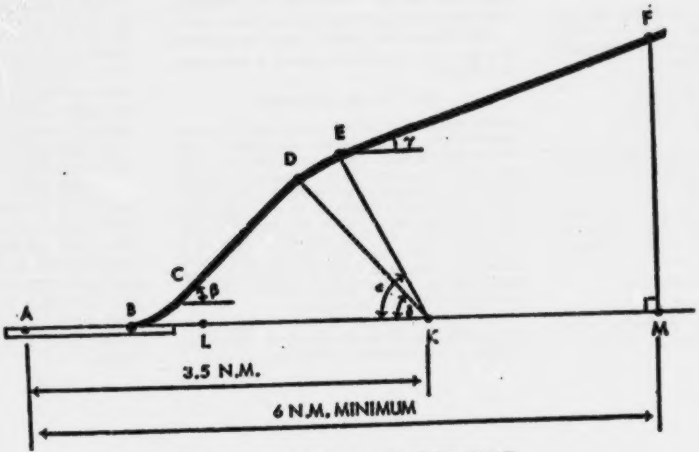

F
E
γ
D
C
β
A
B
L
ε
δ
K
M
3.5 N.M.
6 N.M. MINIMUM

FIGURE A2. MEASURED TAKEOFF PROFILE.

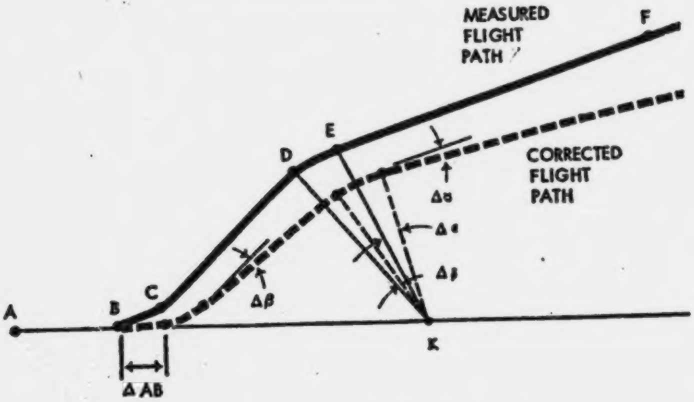

MEASURED
FLIGHT
PATH
F
E
D
CORRECTED
FLIGHT
PATH
Δα
Δε
Δδ
C
Δβ
A
B
K
Δ AB

FIGURE A3. COMPARISON OF MEASURED AND
CORRECTED TAKEOFF PROFILES.

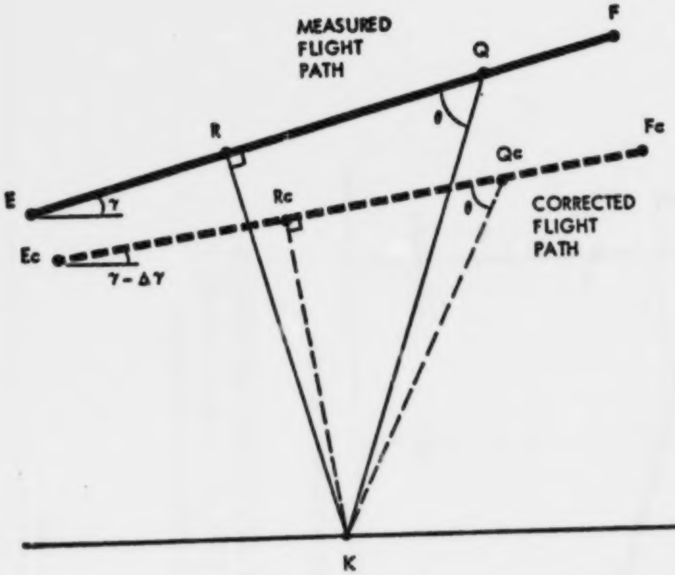

MEASURED
FLIGHT
PATH
F
Q
R
E
γ
θ
Fc
Qc
Rc
θ
CORRECTED
FLIGHT
PATH
Ec
γ - Δγ
K

FIGURE A4. TAKEOFF PROFILE CHARACTERISTICS INFLUENCING SOUND PROPAGATION.

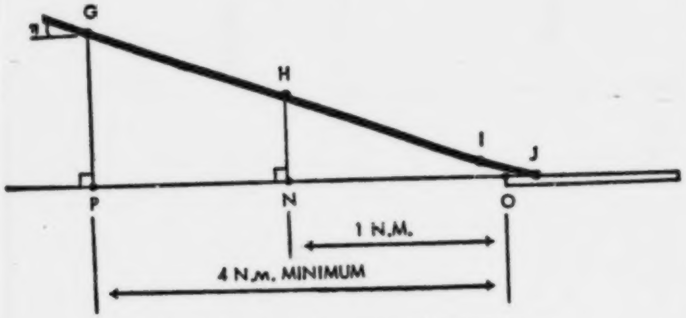

G
H
I
J
P
N
O
1 N.M.
4 N.M. MINIMUM

FIGURE A5. MEASURED APPROACH PROFILE.

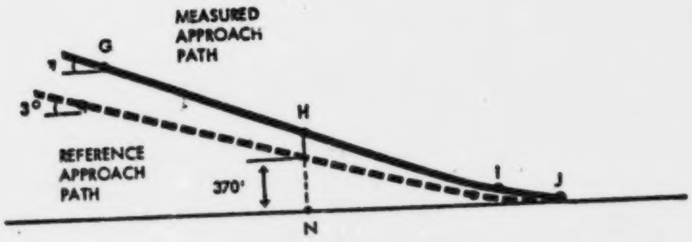

MEASURED
APPROACH
PATH
G
3°
H
REFERENCE
APPROACH
PATH
370'
I
J
N

FIGURE A6. COMPARISON OF MEASURED AND CORRECTED APPROACH PROFILES.

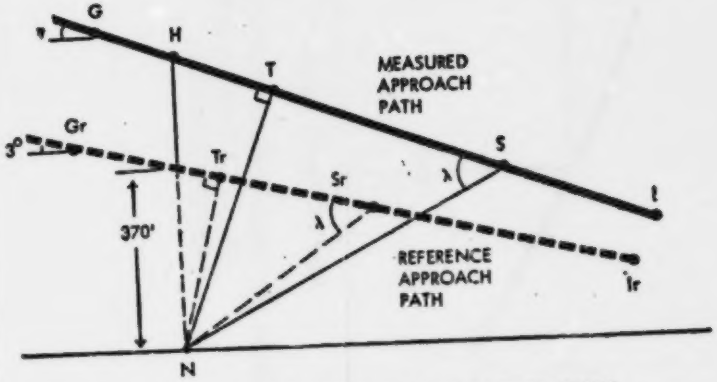

G
H
T
MEASURED
APPROACH
PATH
S
I
3°
Gr
Tr
Sr
λ
λ
370'
REFERENCE
APPROACH
PATH
Ir
N

FIGURE A7. APPROACH PROFILE CHARACTERISTICS INFLUENCING SOUND PROPAGATION.

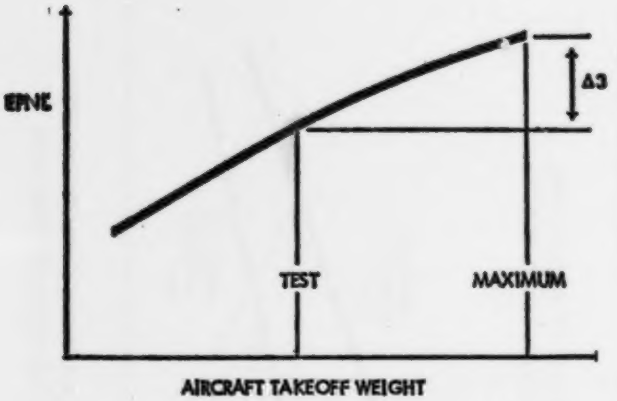


FIGURE A8. TAKEOFF WEIGHT CORRECTION FOR EPNL AT 3.5 NAUTICAL MILES FROM BRAKE RELEASE.

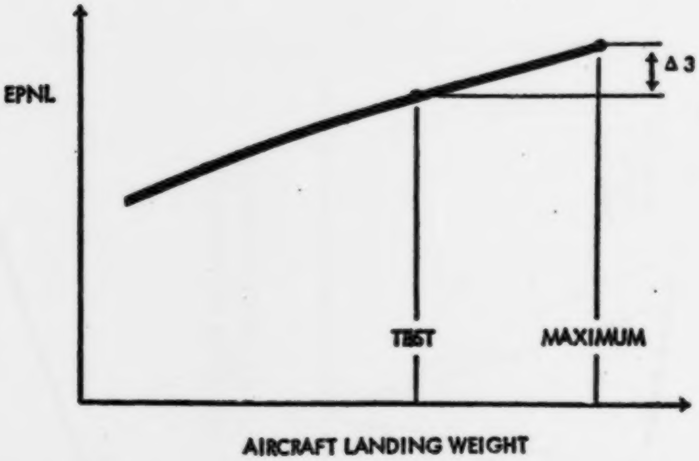


FIGURE A9. APPROACH WEIGHT CORRECTION FOR EPNL AT 1.0 NAUTICAL MILE FROM RUNWAY THRESHOLD.

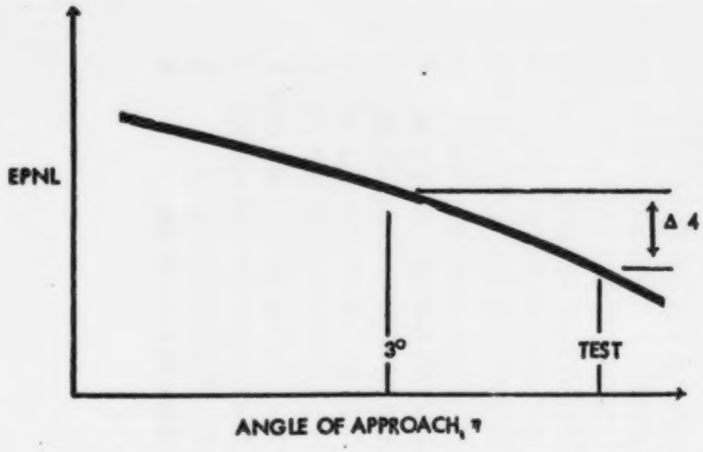


FIGURE A10. APPROACH ANGLE CORRECTION FOR EPNL AT 1.0 NAUTICAL MILE FROM RUNWAY THRESHOLD.

APPENDIX B—AIRCRAFT NOISE EVALUATION UNDER § 36.103

Section B36.1 *General.* The procedures in this appendix must be used to determine the noise evaluation quantity designated as effective perceived noise level, EPNL, under § 36.103. These procedures, which use the physical properties of noise measured as prescribed by Appendix A of this part, consist of the following:

(a) The 24 one-third octave bands of sound pressure level are converted to perceived noisiness by means of a noy table. The noy values are combined and then converted to instantaneous perceived noise levels, PNL(k).

(b) A tone correction factor, C(k), is calculated for each spectrum to account for the subjective response to the presence of the maximum tone.

(c) The tone correction factor is added to the perceived noise level to obtain tone corrected perceived noise levels, PNLT(k), at each one-half second increment of time. The instantaneous values of tone corrected perceived noise level are noted with respect to time and the maximum value, PNLTM, is determined.

$$PNLT(k) = PNL(k) + C(k)$$

(d) A duration correction factor, D, is computed by integration under the curve of tone corrected perceived noise level versus time.

(e) Effective perceived noise level, EPNL, is determined by the algebraic sum of the maximum tone corrected perceived noise level and the duration correction factor.

$$EPNL = PNLTM + D$$

Section B36.2 *Perceived noise level.* Instantaneous perceived noise levels, PNL(k), must be calculated from instantaneous one-third octave band sound pressure levels, SPL(i,k), as follows:

Step 1. Convert each one-third octave band SPL(i,k), from 50 to 10,000 Hz, to perceived noisiness, n(i,k), by reference to Table B1, or to the mathematical formulation of the noy table given in § B36.7 of this appendix.

Step 2. Combine the perceived noisiness values, n(i,k), found in step 1 by the following formula:

$$N(k) = n(k) + 0.15 \left[\left[\sum_{i=1}^{24} n(i, k) \right] - n(k) \right]$$

$$= 0.85n(k) + 0.15 \sum_{i=1}^{24} n(i, k)$$

where n(k) is the largest of the 24 values of n(i,k) and N(k) is the total perceived noisiness.

Step 3. Convert the total perceived noisiness, N(k), into perceived noise level, PNL(k), by the following formula:

$$PNL(k) = 40.0 + 33.3 \log N(k)$$

which is plotted in Figure B1. PNL(k) may also be obtained by choosing N(k) in the 1,000 Hz column of Table B1 and then reading the corresponding value of SPL(i,k) which, at 1,000 Hz, equals PNL(k).

SPL dB

One-Third Octave Band Center Frequencies f, HZ

Table B1. Perceived Noisiness (NOYs) as a Function of Sound Pressure Level.

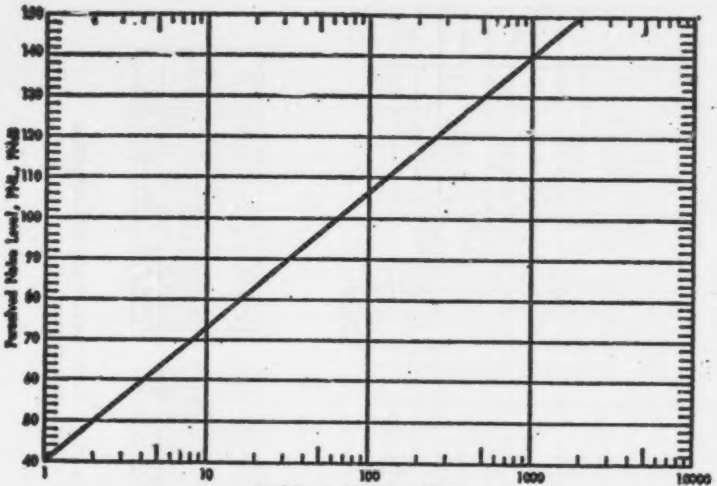


Figure 31. Perceived Noise Level as a Function of Noys.

Section B36.3 *Correction for spectral irregularities.* Noise having pronounced irregularities in the spectrum (for example, discrete frequency components or tones), must be adjusted by the correction factor $C(k)$ calculated as follows:

Step 1. Starting with the corrected sound pressure level in the 80 Hz one-third octave band (band number 3), calculate the changes in sound pressure level (or "slopes") in the remainder of the one-third octave bands as follows:

$$s(3,k) = \text{no value}$$
$$s(4,k) = SPL(4,k) - SPL(3,k)$$
$$\vdots$$
$$s(i,k) = SPL(i,k) - SPL[(i-1),k]$$
$$\vdots$$
$$s(24,k) = SPL(24,k) - SPL(23,k)$$

Step 2. Encircle the value of the slope, $s(i,k)$, where the absolute value of the change in slope is greater than 5; that is, where

$$|\Delta s(i,k)| = |s(i,k) - s[(i-1),k]| > 5.$$

Step 3. (a) If the encircled value of the slope $s(i,k)$ is positive and algebraically greater than the slope $s[(i-1),k]$, encircle $SPL(i,k)$.

(b) If the encircled value of the slope $s(i,k)$ is zero or negative and the slope $s[(i-1),k]$ is positive, encircle $(SPL[(i-1),k])$

(c) For all other cases, no sound pressure level value is to be encircled.

Step 4. Omit all $SPL(i,k)$ encircled in Step 3 and compute new sound pressure levels $SPL'(i,k)$ as follows:

(a) For nonencircled sound pressure levels, let the new sound pressure levels equal the original sound pressure levels,

$$SPL'(i,k) = SPL(i,k)$$

(b) For encircled sound pressure levels in bands 1–23, let the new sound pressure level equal the arithmetic average of the preceding and following sound pressure levels,

$$SPL'(i,k) = (1/2)[SPL[(i-1),k] + SPL[(i+1),k]]$$

(c) If the sound pressure level in the highest frequency band ($i=24$) is encircled, let the new sound pressure level in that band equal

$$SPL'(24,k) = SPL(23,k) + s(23,k).$$

Step 5. Recompute new slopes $s'(i,k)$, including one for an imaginary 25-th band, as follows:

$$s'(3,k) = s'(4,k)$$
$$s'(4,k) = SPL'(4,k) - SPL'(3,k)$$
$$\vdots$$
$$s'(i,k) = SPL'(i,k) - SPL'[(i-1),k]$$
$$\vdots$$
$$s'(24,k) = SPL'(24,k) - SPL'(23,k)$$
$$s'(25,k) = s'(24,k)$$

Step 6. For i from 3 to 23, compute the arithmetic average of the three adjacent slopes as follows:

$$\bar{s}(i,k) = (1/3)[s'(i,k) + s'[(i+1),k] + s'[(i+2),k]]$$

Step 7. Compute final adjusted one-third octave-band sound pressure levels, $SPL''(i,k)$, by beginning with band number 3 and proceeding to band number 24 as follows:

$$SPL''(3,k) = SPL(3,k)$$
$$SPL''(4,k) = SPL''(3,k) + \bar{s}(3,k)$$
$$\vdots$$
$$SPL''(i,k) = SPL''[(i-1),k] + \bar{s}[(i-1),k]$$
$$\vdots$$
$$SPL''(24,k) = SPL''(23,k) + \bar{s}(23,k)$$

Step 8. Calculate the differences, $F(i,k)$, between the original and the adjusted sound pressure levels as follows:

$$F(i,k) = SPL(i,k) - SPL''(i,k)$$

and note only values greater than zero.

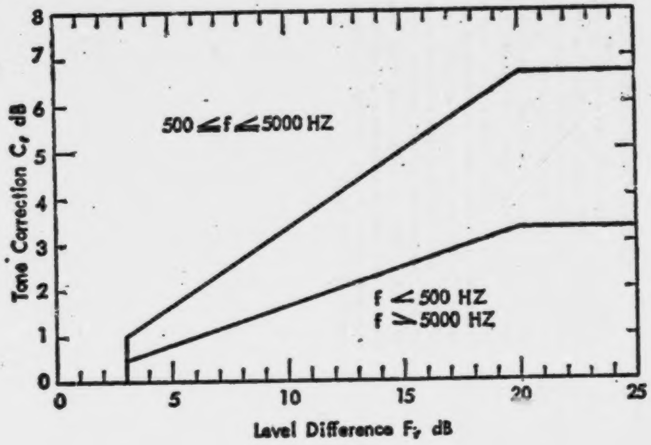
Step 9. For each of the 24 one-third octave bands, determine tone correction factors from the sound pressure level differences $F(i,k)$ and Table B2.

Step 10. Designate the largest of the tone correction factors, determined in Step 9, as $C(k)$. An example of the tone correction procedure is given in Table B3.

Tone corrected perceived noise levels $PNLT(k)$ are determined by adding the $C(k)$ values to corresponding $PNL(k)$ values, that is,

$$PNLT(k) = PNL(k) + C(k)$$

For any i-th one-third octave band, at any k-th increment of time, for which the tone correction factor is suspected to result from something other than (or in addition to) an actual tone (or any spectral irregularity other than aircraft noise), an additional analysis may be made using a filter with a bandwidth narrower than one-third of an octave. If the narrow band analysis corroborates that suspicion, then a revised value for the background sound pressure level, $SPL''(i,k)$, may be determined from the analysis and used to compute a revised tone correction factor, $F(i,k)$, for that particular one-third octave band.



Frequency f, HZ	Level Difference F, dB	Tone Correction C, dB
50 ≤ f < 500	F < 3 3 ≤ F < 20 20 ≤ F	0 F/6 3 1/3
500 ≤ f ≤ 5000	F < 3 3 ≤ F < 20 20 ≤ F	0 F/3 6 2/3
5000 < f ≤ 10000	F < 3 3 ≤ F < 20 20 ≤ F	0 F/6 3 1/3

Table B2.. Tone Correction Factors

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
Band (i)	f HZ	SPL dB	S dB Step 1	|ΔS| dB Step 2	SPL' dB Step 4	S' dB Step 5	$\overline{S}$ dB Step 6	SPL" dB Step 7	F dB Step 8	C, dB Step 9
1	50	-	-	-	-	-	-	-	-	-
2	63	-	-	-	-	-	-	-	-	-
3	80	70	-	-	70	-8	-2 1/3	70	-	
4	100	62	- 8	-	62	-8	+3 1/3	67 2/3	-	
5	125	(70)	+⑧	16	71	+9	+6 2/3	71	-	
6	160	80	+10	2	80	+9	+2 2/3	77 2/3	2 1/3	
7	200	82	+②	8	82	+2	-1 1/3	80 1/3	1 2/3	
8	250	(83)	+ 1	1	79	-3	-1 1/3	79	4	2/3
9	315	76	-⑦	8	76	-3	+ 1/3	77 2/3	-	
10	400	(80)	+④	11	78	+2	+1	78	2	
11	500	80	0	4	80	+2	0	79	1	
12	630	79	- 1	1	79	-1	0	79	-	
13	800	78	- 1	0	78	-1	- 1/3	79	-	
14	1000	80	+ 2	3	80	+2	- 2/3	78 2/3	1 1/3	
15	1250	78	- 2	4	78	-2	- 1/3	78	-	
16	1600	76	- 2	0	76	-2	+ 1/3	77 2/3	-	
17	2000	79	+ 3	5	79	+3	+1	78	1	
18	2500	(85)	+ 6	3	79	0	- 1/3	79	6	$\boxed{2}$
19	3150	79	-⑥	12	79	0	-2 2/3	78 2/3	1/3	
20	4000	78	- 1	5	78	-1	-6 1/3	76	2	
21	5000	71	-⑦	6	71	-7	-8	69 2/3	1 1/3	
22	6300	60	-11	4	60	-11	-8 2/3	61 2/3	-	
23	8000	54	- 6	5	54	-6	-8	53	1	0
24	10000	45	- 9	3	45	-9	-	45	-	
						-9				

Step 1	③ (i) - ③ (i-1)
Step 2	|④ (i) - ④ (i-1)|
Step 3	see instructions
Step 4	see instructions
Step 5	⑥ (i) - ⑥ (i-1)

Step 6	[⑦ (i) + ⑦ (i+1) + ⑦ (i+2)] ÷ 3
Step 7	⑨ (i-1) + ⑧ (i-1)
Step 8	③ (i) - ⑨ (i)
Step 9	see Table B2

Table B3. Example of Tone Correction Calculation for a Turbofan Engine

Section B36.4 *Maximum tone corrected perceived noise level.* The maximum tone corrected perceived noise level, PNLTM, is the maximum calculated value of the tone corrected perceived noise level, PNLT(k), calculated in accordance with the procedure of § B36.3 of this Appendix. Figure B2 is an example of a flyover noise time history where the maximum value is clearly indicated. Half-second time intervals, Δt, are small enough to obtain a satisfactory noise time history.

If there are no pronounced irregularities in the spectrum, then the procedure of § B36.3 of this Appendix would be redundant since PNLT(k) would be identically equal to PNL(k). For this case, PNLTM would be the maximum value of PNL(k) and would equal PNLM.

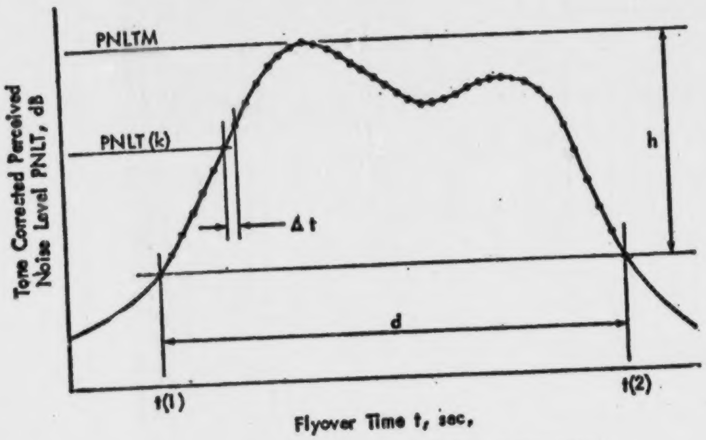


Figure B2. Example of Perceived Noise Level Corrected for Tones as a Function of Aircraft Flyover Time

Section B36.5 *Duration correction.* The duration correction factor D is determined by the integration technique defined by the expression:

$$D=10\log\left[(1/T)\int_{t(1)}^{t(2)}\text{ant}\,[\text{PNLT}/10]\,dt\right]-\text{PNLTM}$$

where T is a normalizing time constant, PNLTM is the maximum value of PNLT, and t(1) and t(2) are the limits of the significant noise time history.

Since PNLT is calculated from measured values of SPL, there will, in general, be no obvious equation for PNLT as a function of time. Consequently, the equation can be re-written with a summation sign instead of an integral sign as follows:

$$D=10\log\left[(1/T)\sum_{k=0}^{d/\Delta t}\Delta t\,\text{ant}\,[\text{PNLT}(k)/10]\right]-\text{PNLTM}$$

where Δt is the length of the equal increments of time for which PNLT(k) is calculated and d is the time interval to the nearest 1.0 second during which PNLT(k) is within a specified value, h, of PNLTM.

Half-second time intervals for Δt are small enough to obtain a satisfactory history of the perceived noise level. A shorter time interval may be selected by the applicant provided aproved limits and constants are used.

The following values for T, Δt, and h, must be used in calculating D:

$$T=10\text{ sec,}$$
$$\Delta t=0.5\text{ sec, and}$$
$$h=10\text{ dB.}$$

Using the above values, the equation for D becomes

$$D=10\log\left[\sum_{k=0}^{2d}\text{ant}\,[\text{PNLT}(k)/10]\right]-\text{PNLTM}-13$$

where the integer d is the duration time defined by the points that are 10 dB less than PNLTM.

If the 10 dB-down points fall between calculated PNLT(k) values (the usual case), the applicable limits for the duration time must be chosen from the PNLT(k) values closest to PNLTM−10. For those cases with more than one peak value of PNLT(k), the applicable limits must be chosen to yield the largest possible value for the duration time.

If the value of PNLT(k) at the 10 dB-down points is 90 PNdB or less, the value of d may be taken as the time interval between the initial and the final times for which PNLT(k) equals 90 PNdB.

Section B36.6 *Effective perceived noise level.* The total subjective effect of an aircraft flyover is designated "effective perceived noise level," EPNL, and is equal to the algebraic sum of the maximum value of the tone corrected perceived noise level, PNLTM, and the duration correction, D. That is,

$$\text{EPNL}=\text{PNLTM}+D$$

where PNLTM and D are calculated under §§ B36.4 and B36.5 of this appendix.

The above equation can be rewritten by substituting the equation for D from § B36.5 of this appendix, that is,

$$\text{EPNL}=10\log\left[\sum_{k=0}^{2d}\text{ant}\,[\text{PNLT}(k)/10]\right]-13$$

Section B36.7 *Mathematical formulation of noy tables.* The relationship between sound pressure level and perceived noisiness given in Table B1 is illustrated in Figure B3. The variation of SPL with log n for a given one-third octave band can be expressed by either one or two straight lines depending upon the frequency range. Figure B3(a) illustrates the double line case for frequencies below 400 Hz, and above 6,300 Hz and Figure B3(b) illustrates the single line case for all other frequencies.

The important aspects of the mathematical formulation are:

1. the slopes of the straight lines, p(b) and p(c),
2. the intercepts of the lines on the SPL-axis, SPL(b), and SPL(c), and
3. the coordinates of the discontinuity, SPL(a), and log n(a).

The equations are as follows:

Case 1. Figure B3(a), $f < 400$ Hz.
$f > 6300$ Hz.

$$\text{SPL}(a)=\frac{p(c)\,\text{SPL}(b)-p(b)\,\text{SPL}(c)}{p(c)-p(b)}$$

$$\log n(a)=\frac{\text{SPL}(c)-\text{SPL}(b)}{p(b)-p(c)}$$

(a) $\text{SPL}(b)\le\text{SPL}\le\text{SPL}(a)$.

$$n=\text{ant}\,\frac{\text{SPL}-\text{SPL}(b)}{p(b)}$$

(b) $\text{SPL}\ge\text{SPL}(a)$.

$$n=\text{ant}\,\frac{\text{SPL}-\text{SPL}(c)}{p(c)}$$

(c) $0\le\log n\le\log n(a)$.
$\text{SPL}=p(b)\log n+\text{SPL}(b)$

(d) $\log n\ge\log n(a)$.
$\text{SPL}=p(c)\log n+\text{SPL}(c)$

Case 2. Figure B3(b), $400\le f\le 6300$ Hz.

(a) $\text{SPL}\ge\text{SPL}(c)$.

$$n=\text{ant}\,\frac{\text{SPL}-\text{SPL}(c)}{p(c)}$$

(b) $\log n\ge 0$.
$\text{SPL}=p(c)\log n+\text{SPL}(c)$

Let the reciprocals of the slopes be defined as,

$$M(b)=1/p(b)$$
$$M(c)=1/p(c)$$

Then the equations can be written,

Case 1. Figure B3(a), $f<400$ Hz.
$f>6300$ Hz.

$$\text{SPL}(a)=\frac{M(b)\,\text{SPL}(b)-M(c)\,\text{SPL}(c)}{M(b)-M(c)}$$

$$\log n(a)=\frac{M(b)\,M(c)\,[\text{SPL}(c)-\text{SPL}(b)]}{M(c)-M(b)}$$

(a) $\text{SPL}(b)\le\text{SPL}\le\text{SPL}(a)$.
$n=\text{ant}\,M(b)\,[\text{SPL}-\text{SPL}(b)]$

(b) $\text{SPL}\ge\text{SPL}(a)$.
$n=\text{ant}\,M(c)\,[\text{SPL}-\text{SPL}(c)]$

(c) $0\le\log n\le\log n(a)$.

$$\text{SPL}=\frac{\log n}{M(b)}+\text{SPL}(b)$$

(d) $\log n\ge\log n(a)$.

$$\text{SPL}=\frac{\log n}{M(c)}+\text{SPL}(c)$$

Case 2. Figure B3(b), $400\le f\le 6300$ Hz.

(a) $\text{SPL}\ge\text{SPL}(c)$.
$n=\text{ant}\,M(c)\,[\text{SPL}-\text{SPL}(c)]$

(b) $\log n\ge 0$.

$$\text{SPL}=\frac{\log n}{M(c)}+\text{SPL}(c)$$

Table B1 lists the values of the important constants necessary to calculate sound pressure level as a function of perceived noisiness.

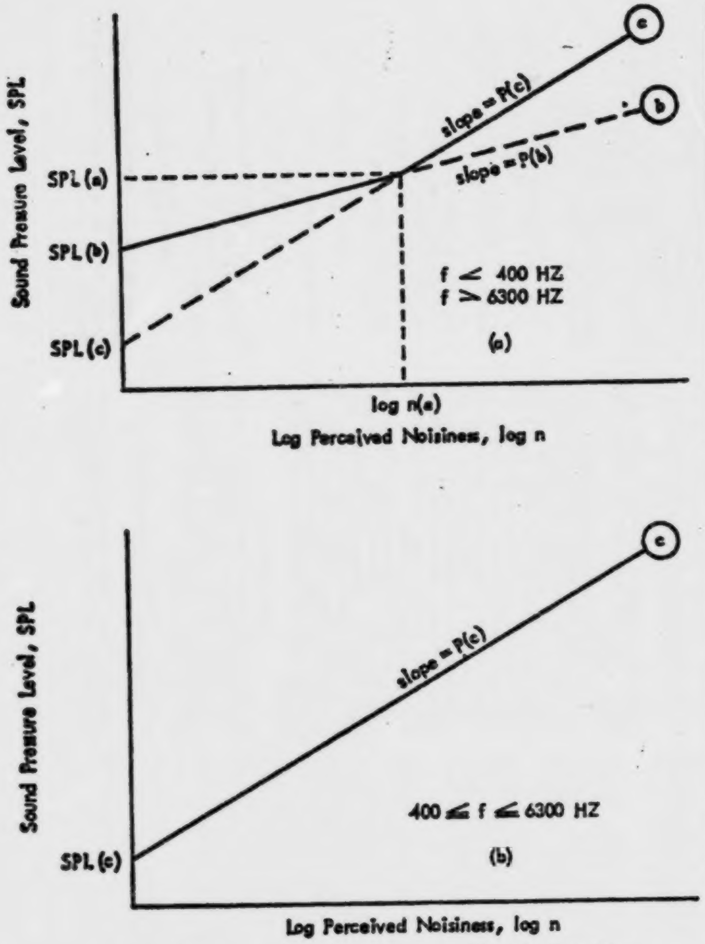


Figure 33. Sound Pressure Level as a Function of Noys.

Band (i)	f HZ	M(b)	SPL (b) dB	SPL (a) dB	M(c)	SPL (c) dB
1	50	0.043478	64	91.0	0.030103	52
2	63	0.040570	60	85.9	"	51
3	80	0.036831	56	87.3	"	49
4	100	"	53	79.9	"	47
5	125	0.035336	51	79.8	"	46
6	160	0.033333	48	76.0	"	45
7	200	"	46	74.0	"	43
8	250	0.032051	44	74.9	"	42
9	315	0.030675	42	94.6	"	41
10	400	-	-	-	"	40
11	500	-	-	-	"	"
12	630	-	-	-	"	"
13	800	-	-	-	"	"
14	1000	-	-	-	"	"
15	1250	-	-	-	"	38
16	1600	-	-	-	0.029960	34
17	2000	-	-	-	"	32
18	2500	-	-	-	"	30
19	3150	-	-	-	"	29
20	4000	-	-	-	"	"
21	5000	-	-	-	"	30
22	6300	-	-	-	"	31
23	8000	0.042285	37	44.3	"	34
24	10000	"	41	50.7	"	37

Table B4. Constants for Mathematically Formulated NOY Values

APPENDIX C—NOISE LEVELS FOR SUBSONIC TRANSPORT CATEGORY AND TURBOJET POWERED AIRPLANES UNDER § 36.201

Section C36.1 *Noise measurement and evaluation.* Compliance with this appendix must be shown with noise levels measured and evaluated as prescribed, respectively, by Appendix A and Appendix B of this part, or under approved equivalent procedures.

Section C36.3 *Noise measuring points.* Compliance with the noise level standards of § C36.5 must be shown—

(a) For takeoff, at a point 3.5 nautical miles from the start of the takeoff roll on the extended centerline of the runway;

(b) For approach, at a point 1 nautical mile from the threshold on the extended centerline of the runway; and

(c) For the sideline, at the point, on a line parallel to and 0.25 nautical miles from the extended centerline of the runway, where the noise level after liftoff is greatest, except that, for airplanes powered by more than three turbojet engines, this distance must be 0.35 nautical miles.

Section C36.5 *Noise levels*—(a) *General.* Except as provided in paragraphs (b) and (c) of this section, it must be shown by flight test that the noise levels of the airplane, at the measuring points prescribed in § 36.3, do not exceed the following (with appropriate interpolation between weights):

(1) For approach and sideline, 108 EPNdB for maximum weights of 600,000 pounds or more, less 2 EPNdB per halving of the 600,000-pound maximum weight down to 102 EPNdB for maximum weights of 75,000 pounds and under.

(2) For takeoff, 108 EPNdB for maximum weights of 600;000 pounds or more, less 5 EPNdB per halving of the 600,000-pound maximum weight down to 93 EPNdB for maximum weights of 75,000 pounds and under.

(b) *Tradeoff.* The noise levels in paragraph (a) may be exceeded at one or two of the measuring points prescribed in § C36.3, if—

(1) The sum of the exceedances is not greater than 3 EPNdB;

(2) No exceedance is greater than 2 EPNdB; and

(3) The exceedances are completely offset by reductions at other required measuring points.

(c) *Prior applications.* For applications made before December 1, 1969, for airplanes powered by more than three turbojet engines with bypass ratios of two or more, the value prescribed in paragraph (b)(1) of this section may not exceed 5 EPNdB and the value prescribed in paragraph (b)(2) of this section may not exceed 3 EPNdB.

Section C36.7 *Takeoff test conditions.* (a) This section applies to all takeoffs conducted in showing compliance with this part.

(b) Takeoff power or thrust must be used from the start of the takeoff to the point at which an altitude of at least 1,000 feet above the runway is reached, except that, for airplanes powered by more than three turbojet engines, this altitude must not be less than 700 feet.

(c) Upon reaching the altitude specified in paragraph (b) of this section, the power or thrust may not be reduced below that power or thrust that will provide level flight with one engine inoperative, or below that power or thrust that will maintain a climb gradient of at least 4 percent, whichever power or thrust is greater.

(d) A speed of at least V_2+10 knots must be attained as soon as practicable after lift-off, and must be maintained throughout the takeoff noise test.

(e) A constant takeoff configuration, selected by the applicant, must be maintained throughout the takeoff noise test.

Section C36.9 *Approach test conditions.* (a) This section applies to all approaches conducted in showing compliance with this part.

(b) The airplane's configuration must be that specified by the applicant.

(c) The approaches must be conducted with a steady glide angle of 3° ± 0.5° and must be continued to a normal touchdown with no airframe configuration change.

(d) A steady approach speed of not less than $1.30\ V_s+10$ knots must be established and maintained over the approach measuring point.

(e) All engines must be operating at approximately the same power or thrust, and must be operating at not less than the power or thrust required for the maximum allowable flap setting.

[F.R. Doc. 69-13368; Filed, Nov. 17, 1969; 9:08 a.m.]

(As published in the Federal Register [34 F.R. 18355] on Nov. 18, 1969)

Title 14—AERONAUTICS AND SPACE

Chapter I—Federal Aviation Administration, Department of Transportation

[Docket No. 9993; Amdt. 36-1]

PART 36—NOISE STANDARDS: AIRCRAFT TYPE CERTIFICATION

Approach Noise Test Conditions

This amendment changes the type certification approach noise test conditions for subsonic transport category airplanes and for subsonic turbojet powered airplanes regardless of category. The purpose of this amendment is to insure that the approach noise type certification test (1) is conducted with the same airplane configuration as that used during airworthiness type certification; and (2) does not result in noise levels less than those that will be generated by the airplane in normal operation.

Part 36, *Noise standards: Aircraft type certification* was issued by the Administrator on November 3, 1969, and will be effective on December 1, 1969. Section C36.9 of Appendix C of that part contains the test conditions applicable to all approaches conducted in showing compliance with Part 36. That section contains two provisions that require amendment when Part 36 becomes effective.

First, paragraph (b) of section C36.9 currently provides that the airplane's configuration must be "that specified by the applicant." It now appears that this language could be regarded as permitting the applicant to specify configurations that are not the same as those used in showing compliance with the landing requirements in the airworthiness regulations. This result is not intended. While the general requirement of compatibility between noise and airworthiness type certification test conditions and procedures includes approach noise test conditions and procedures, it is believed advisable to remove any question that may be caused by section C36.9(b). Therefore, that paragraph is amended to specifically provide, in part, that the airplane's configuration during the approach noise test must be "that used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane."

Second, paragraph (e) of section C36.9 currently provides that the approach noise test must be conducted with engines operating at not less than the "power or thrust required for the maximum allowable flap setting." The intent of this provision is to ensure that the noise generated during the approach noise type certification test will not be less than that later generated by the airplane in normal operation. However, configuration aspects other than flaps may affect the noise of the airplane. In addition, there is no need to specify a particular power or thrust once a specified configuration is identified since section C36.9 also specifies the glide angle and minimum approach speed, requires that both be "steady," and requires that the approach be continued to a normal touchdown with no configuration change. In the light of the above, it is believed that the objective of ensuring that approaches made later in normal operation will not be noisier than the published noise levels of the airplane can be more effectively achieved by providing, in section C36.9(b), that "if more than one configuration is used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane, the configuration that is most critical from a noise standpoint must be used" in showing compliance with the approach noise requirements of Part 36. This amendment is necessary to ensure that the approach noise levels generated by the airplane during type certification will be representative of approach noise levels generated in normal operations.

This amendment is issued in full consideration of comments received with respect to Notice 69-1, issued on January 3, 1969 (34 F.R. 453), including consideration of economic data submitted by affected aircraft manufacturers and operators, and has been determined to be economically reasonable, technologically practicable, and appropriate to the aircraft to which it applies.

Pursuant to section 611 of the Federal Aviation Act of 1958 (49 U.S.C. 1431) the Administrator has consulted with the Secretary of Transportation concerning the matters contained herein, prior to the adoption of this amendment.

Like Part 36, which becomes effective on December 1, 1969, this amendment to that part applies to airplanes now nearing the completion of the type certification process. Therefore, it is essential that this amendment become effective on the same date as Part 36. Therefore, I hereby find that notice and public procedure, in addition to that already provided by Notice 69-1, is impracticable. In addition, I find, for the reasons stated above, that good cause exists for making this amendment effective on less than 30 days notice after publication thereof in the FEDERAL REGISTER.

In consideration of the foregoing, section C36.9 of Appendix C of Part 36 of the Federal Aviation Regulations which becomes effective on December 1, 1969, is amended, effective on that date, to read as follows:

Section C36.9 *Approach test conditions.* (a) This section applies to all approaches conducted in showing compliance with this part.

(b) The airplane's configuration must be that used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane. If more than one configuration is used in showing compliance with the landing requirements in the airworthiness regulations constituting the type certification basis of the airplane, the configuration that is most critical from a noise standpoint must be used.

(c) The approaches must be conducted with a steady glide angle of 3°±0.5° and must be continued to a normal touchdown with no airframe configuration change.

(d) A steady approach speed of not less than $1.30V_s+10$ knots must be established and maintained over the approach measuring point.

(e) All engines must be operating at approximately the same power or thrust.

(Secs. 313(a), 601, 603, 611, Federal Aviation Act of 1958; 49 U.S.C. 1354, 1421, 1423, 1431; sec. 6(c), Department of Transportation Act, 49 U.S.C. 1655(c))

Issued in Washington, D.C., on November 21, 1969.

J. H. SHAFFER,
Administrator.

[F.R. Doc. 69-14010; Filed, Nov. 21, 1969; 11:53 a.m.]

(As published in the Federal Register
/34 F.R. 18815/ on Nov. 25, 1969)

Title 14—AERONAUTICS AND SPACE

Chapter I—Federal Aviation Administration, Department of Transportation

[Docket No. 9337]

PART 36—NOISE STANDARDS: AIRCRAFT TYPE CERTIFICATION

Corrections

The following corrections are hereby made to the preamble and regulatory material of new Part 36—Noise Standards: Aircraft Type Certification, which was published in the FEDERAL REGISTER on Tuesday, November 18, 1969 (34 F.R. 18355–18379):

(1) On page 18360 of the preamble, the word "noise" was inadvertently omitted from the statement, in the right-hand column, second paragraph, that §§ 21.93(b) and 36.1(c) will insure that noise reduction technology sufficient to achieve Appendix C limits must be applied "before further aircraft growth can occur." The quoted words are hereby corrected to read "before further aircraft noise growth can occur."

(2) On page 18364, paragraph (a) of § 36.2 contains a typographical error in

In § 71.181 (34 F.R. 4637), the New Bern, N.C., transition area is amended

hereby corrected to read: "§ 36.201 (b) and (c)(1)."

(3) On page 18379, paragraph (e) of § C36.7 is not correct as it now stands, and this paragraph is hereby corrected to read as follows:

Section C36.7 *Takeoff test conditions.* * * *

(e) A constant takeoff configuration, selected by the applicant, must be maintained throughout the takeoff noise test, except that the landing gear may be retracted.

Issued in Washington, D.C., on November 24, 1969.

J. H. SHAFFER,
Administrator.

[F.R. Doc. 69-14159; Filed, Nov. 28, 1969; 8:45 a.m.]

(As published in the Federal Register
[34 F.R. 19025] on Nov. 29, 1969)

APPENDIX B

METHODOLOGY FOR IMPACT ANALYSIS

This appendix summarizes the various analytical models and supporting data used in Chapter 4 for evaluating impact of noise from transportation vehicles and from internal combustion engine devices. Emphasis is placed on the former category as the primary source of noise impact in most communities today. Specifically, this appendix summarizes each of the following approaches used for evaluating noise impact.

- total noise energy
- residual noise levels
- single event noise levels for major transportation noise sources as a function of distance
- noise impacted land areas around freeways and airports
- noise impact on operators or passengers of transportation vehicles and internal combustion engine devices.

In addition, a brief glossary of key terminology is presented at the end of this appendix.

B.1 Total Noise Energy

The total A-weighted noise energy produced on an average day by each noise source category was estimated in order to provide one simple way of ranking the potential noise impact of each category. Categories with higher noise levels which exist in greater numbers and are used more hours per day will tend to rank highest in terms of their noise energy. The noise energy for a given category, such as standard passenger automobiles, was estimated by the following expression:

$$E = 10^{-3} N \cdot T \cdot W_a, \quad \text{kilowatt-hours/day} \qquad (1)$$

where N = total number of units

T = Average hours per day usage

W_a = approximate A-weighted noise power, watts and

$$10 \log \frac{W_a}{10^{-13}} = L_A + 20 \log R_o + 7.5 \quad \text{dB re } 10^{-13} \text{ watts}$$

where

L_A = typical A-weighted noise level in dB(A) at a reference distance R_o (in feet).

The four input parameters required for this calculation (N, T, L_A and R_o) are summarized in Table B-1 for all of the categories considered under transportation vehicles and internal combustion engine devices. The values for number of units and usage shown are based on estimated figures for 1970 compiled from available statistical data.[1-10] Where up-to-date figures were not available for 1970, linear extrapolations were made based on available data, or where necessary, engineering estimates made of probable values.

For ground transportation vehicles, the "typical A-weighted noise levels" correspond to average values at a 50-foot distance for the type of vehicle under normal operating conditions at typical speeds. For aircraft, the noise levels correspond to values at a slant distance to the aircraft of 1000 feet and hours of usage were based on estimates of the duration of landing and takeoff operations in the vicinity of airports. Estimates of noise levels were based on the noise level data for all categories cited earlier in Chapters 2 and 3.

For projections of noise energy to the year 2000, extrapolations in usage were made on the basis of historical trends. For example, Figure B-1(a) illustrates the past trends in passenger-miles of urban travel by various transportation vehicles. These figures have been obtained from published data — or estimated from information on vehicle-miles and average passenger loading.[1-6,9] They clearly show the marked increase in travel by the average citizen — primarily by increase in personal travel in the passenger automobile.

This general increase in mobility is summarized in Figure B-1(b) which shows the total urban passenger miles per urban population for all the transportation

Table B-1

Parameters Used to Define Noise Energy for Each Category in 1970

Category	N Number[1]	T Average Use Hours/Day	L_A Noise Level dB(A)	R_o Distance ft
AIRCRAFT (Takeoff Only)				
4-Engine Turbofan	894	0.2[3]	103	1000
2- and 3-Engine Turbofan	1174	0.1[3]	96	
General Aviation	128,900	0.017[3]	77	
Helicopters	16	6	83	1000
HIGHWAY VEHICLES				
Medium and Heavy Duty Trucks	3.64 M[2]	4	84	50
Sports, Compact and Import Cars	23 M	1	75	
Passenger Cars (Standard)	64 M	1	69	
Light Trucks and Pickups	15.3 M	1.5	72	
Motorcycles (Highway)	2.6 M	0.5	82	
City and School Buses	0.38 M	2	73	
Highway Buses	.02 M	4	83	50
RECREATIONAL VEHICLES				
Minicycles, Off-Road Motorcycles	1 M	1	88	50
Snowmobiles	1.6 M	0.2	85	
Outboard Motorboats	5.2M	.05	75	
Inboard Motorboats	.65 M	.5	80	50

Table B-1 (Continued)

Category	N Number[1]	T Average Use Hours/Day	L_A Noise Level dB(A)	R_o Distance Feet
RAIL VEHICLES				
Locomotives	27,100	12	94	50
Freight Trains	10,000	5	85	
High Speed Intercity Trains	2800	6	85	
Existing Rapid Transit Trains	21,000	0.5	87	
Passenger Trains	185	12	83	
Trolley Cars (Old)	300	12	80	
Trolley Cars (New)	1200	12	66	50
INTERNAL COMBUSTION ENGINE DEVICES				
Lawn Mowers	17M	0.1	74	50
Garden Tractors	5 M	.15	78	
Chain Saws	2.5 M	.05	83	
Snow Blowers	0.8 M	.1	85	
Lawn Edgers	3.3 M	.05	78	
Model Aircraft	1 M	.05	78	
Leaf Blowers	0.5 M	.1	76	
Generators	0.55 M	.1	70	
Tillers	3.5 M	.01	69	

[1] Compiled from Ref. 1-4

[2] M = millions

[3] Estimated hours per day while operating on and near airports and noise level is greater than 80 dB(A).

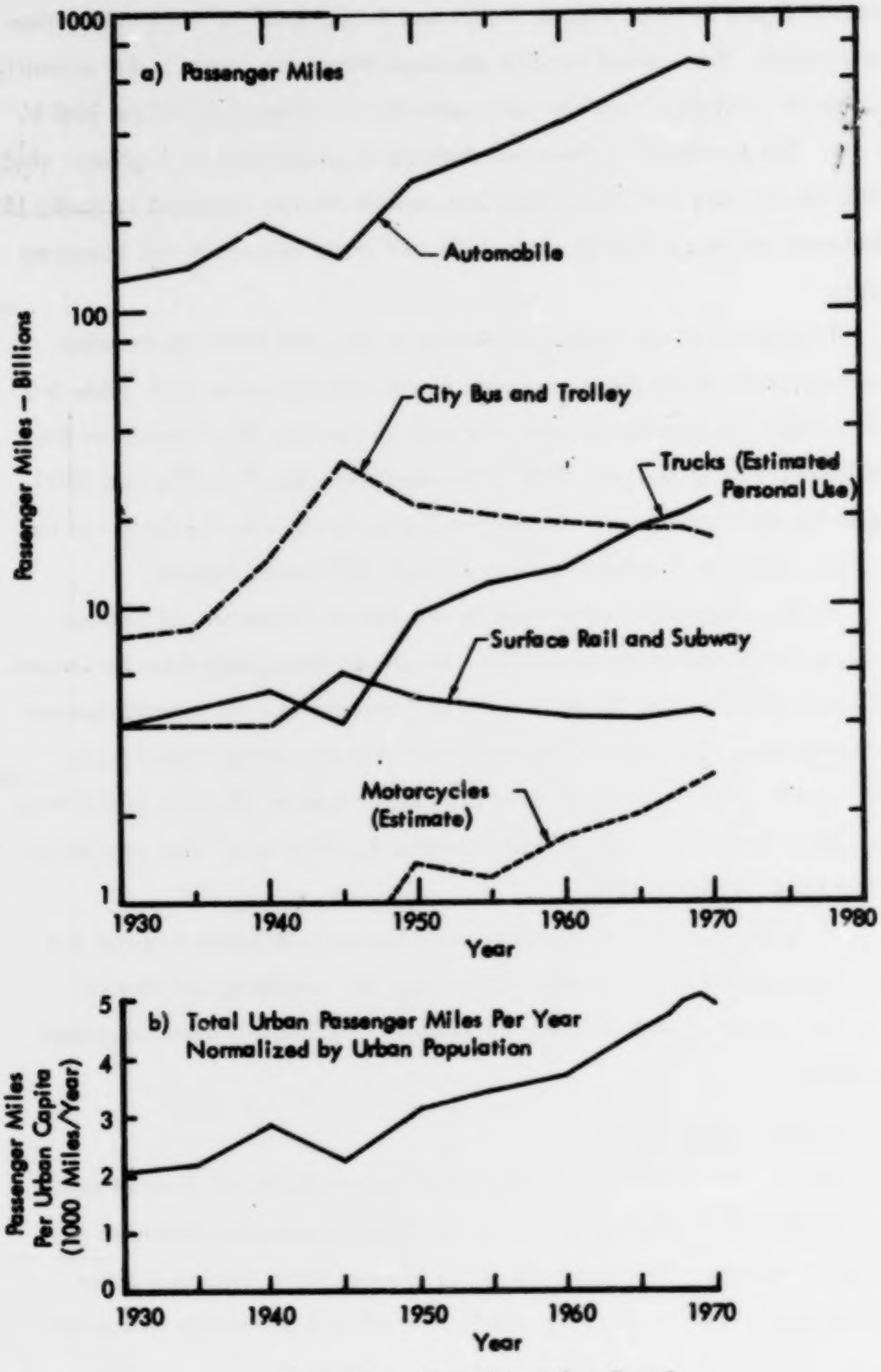


Figure B-1. Growth in Urban Travel
(Compiled or Estimated from Data in References 1–6, 9)

modes shown in Figure B-1(a). Figures B-2(a) and B-2(b) show the same information for intercity travel. This upward trend in passenger travel per capita is due primarily to the increase in numbers of vehicles per capita and not miles traveled per year by each vehicle. The past trend in these two statistics is summarized for highway vehicles in Table B-2 which shows that the mileage per vehicle has not increased markedly in the last 20 years, while numbers of automobiles and trucks per capita has increased substantially.

Projections of the number of vehicles to the year 2000 was therefore made by extrapolation of the trend in number of vehicles per person from Table B-2 taking into account the decrease in rate of growth so that the rate approached the population growth rate by the year 2000. The population growth to the year 2000 was based on the most conservative projection (Series D) made by the Bureau of the Census in 1968, which is in general agreement with 1970 census figures.[1]

Similar projections were made for the change in numbers of internal combustion engine devices to the year 2000. Results of these projections for several of the categories are shown in Figure B-3. It was assumed that the average number of hours of usage per day of each of the categories will not change significantly. Changes in typical noise levels to the year 2000 were made on the basis of the three future noise reduction options, discussed in Chapter 4, which were then applied to the base-line noise levels for 1970.

While the resulting estimates of noise energy (see Tables 4-3 and 4-4 in Chapter 4) are subject to appreciable error, they are considered sufficiently reliable for the purpose of rank-ordering the general magnitude of noise generated by each category.

B.2 Residual Noise Levels

The residual noise level in any area is generated by all forms of traffic moving in and around the community, and by the large number and variety of dispersed stationary sources. The magnitude of the residual noise level in a given community has been shown to vary only slowly if at all in a community with stable

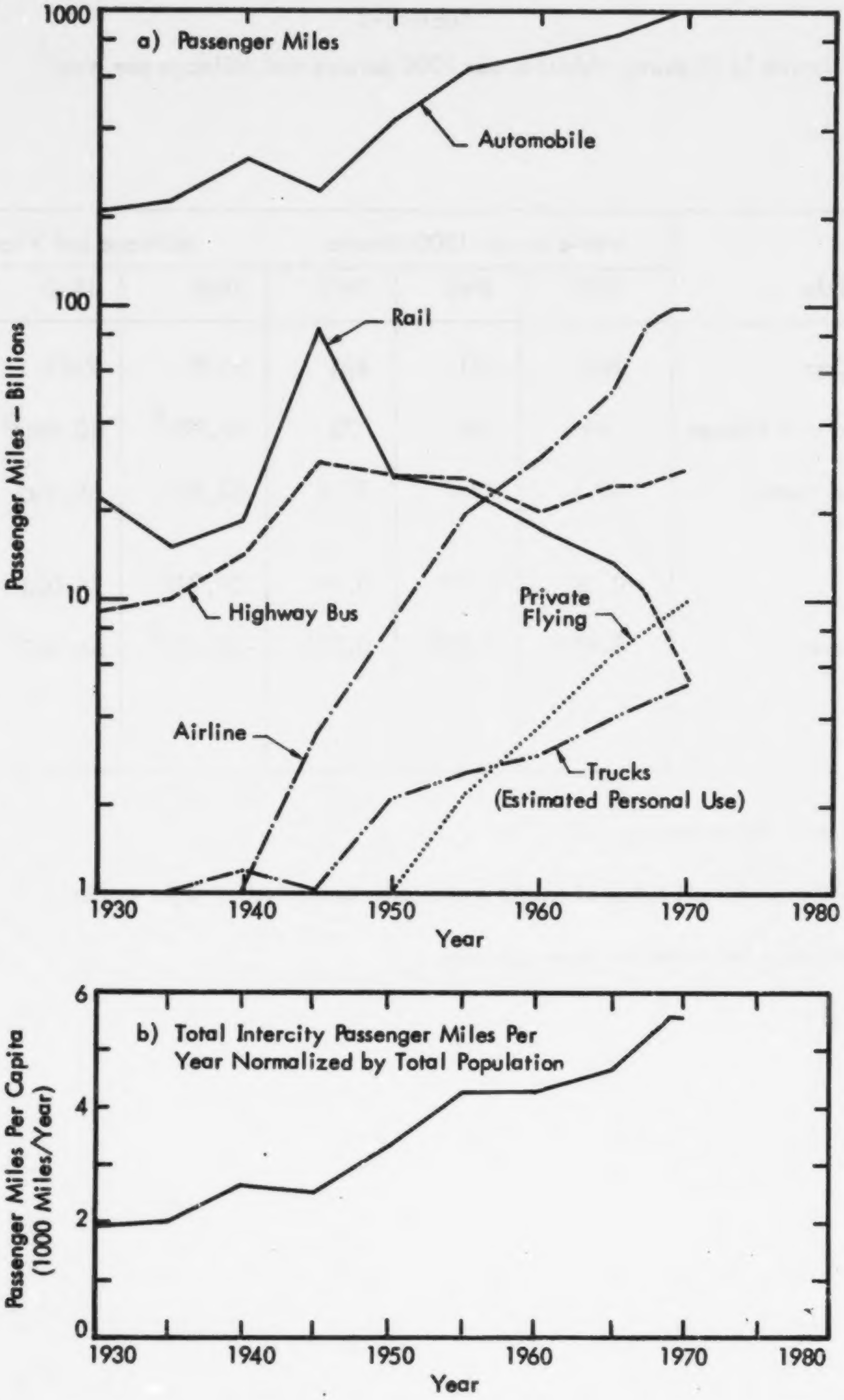


Figure B-2. Growth in Domestic Intercity Travel (Compiled or Estimated from Data in References 1-6, 9)

Table B-2

Trends in Highway Vehicles per 1000 persons and Mileage per Year[1]

Vehicle	Vehicles per 1000 Persons			Mileage per Year		
	1950	1960	1970	1950	1960	1968
Passenger Cars	268	341	426	9078	9474	9507
Light Trucks and Pickups	46	53	75	10,776[2]	10,580[2]	11,570[2]
Medium and Heavy Duty Trucks	10.6	12.7	17.8	53,833	59,590	68,303
City Buses	0.38	0.27	0.24	20,910	16,004	14,122
Highway Buses	0.097	0.070	0.075	65,411[3]	65,567[3]	58,423[3]

[1] Compiled from Reference 1

[2] Average Mileage for all types of trucks which are dominated by light trucks.

[3] Average mileage for intercity motor carriers.

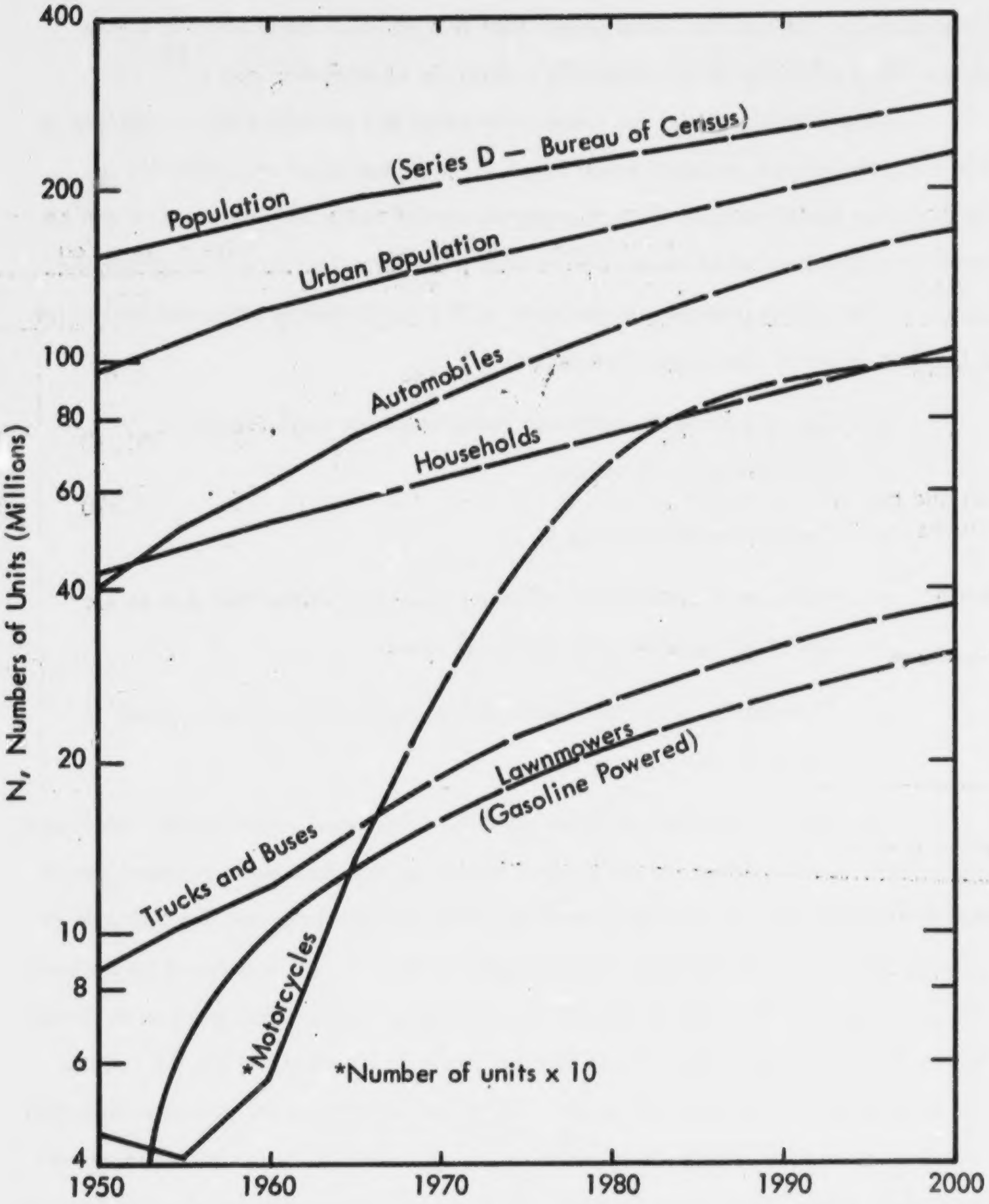


Figure B-3. Growth Trends for Population and Numbers of Several Major Noise Sources Considered for the Noise Impact Analysis. (Compiled and Projected from data in References 1, 2, and 6) land-use patterns. It has also been shown that this residual noise level is a key foundation for evaluation of a community's reaction to intruding noise.[11]

An available model for community noise has therefore been modified to provide estimates of this residual noise level.[12] As illustrated conceptually in Figure B-4, the model assumes that discrete sources of noise in a community can be replaced by a distribution of noise sources with a uniform density n throughout the community. The model provides an estimate of the quasi-steady state residual noise level (L_{90}) in terms of four basic parameters:

- The reference A-weighted noise level for each source, L_A, at a reference distance.
- The reference distance R_o.
- The excess attenuation of sound over and above that due to spherical spreading of the sound, and
- The density n of the distributed sources in number of sources per unit area.

The relationship between the residual noise level predicted by this model and the reference noise level for each contributing source (assumed constant) can be defined as follows: For the distribution of discrete sources shown on the left side of Figure B-4, the effective boundary of influence for one source is defined by a circle with an area equal to the area of one of the 6-sided cells bounding each such source. The radius $\overline{R}$ of this equivalent circle can be shown to be equal to $1/\sqrt{\pi n}$ where n is the number of sources per unit area. The noise from the local source within this zone is considered identifiable as a local intruding noise and is not included as part of the residual noise. The latter is made up, then, of the summation of noise from all the other sources outside this local zone so that the residual noise level, expressed

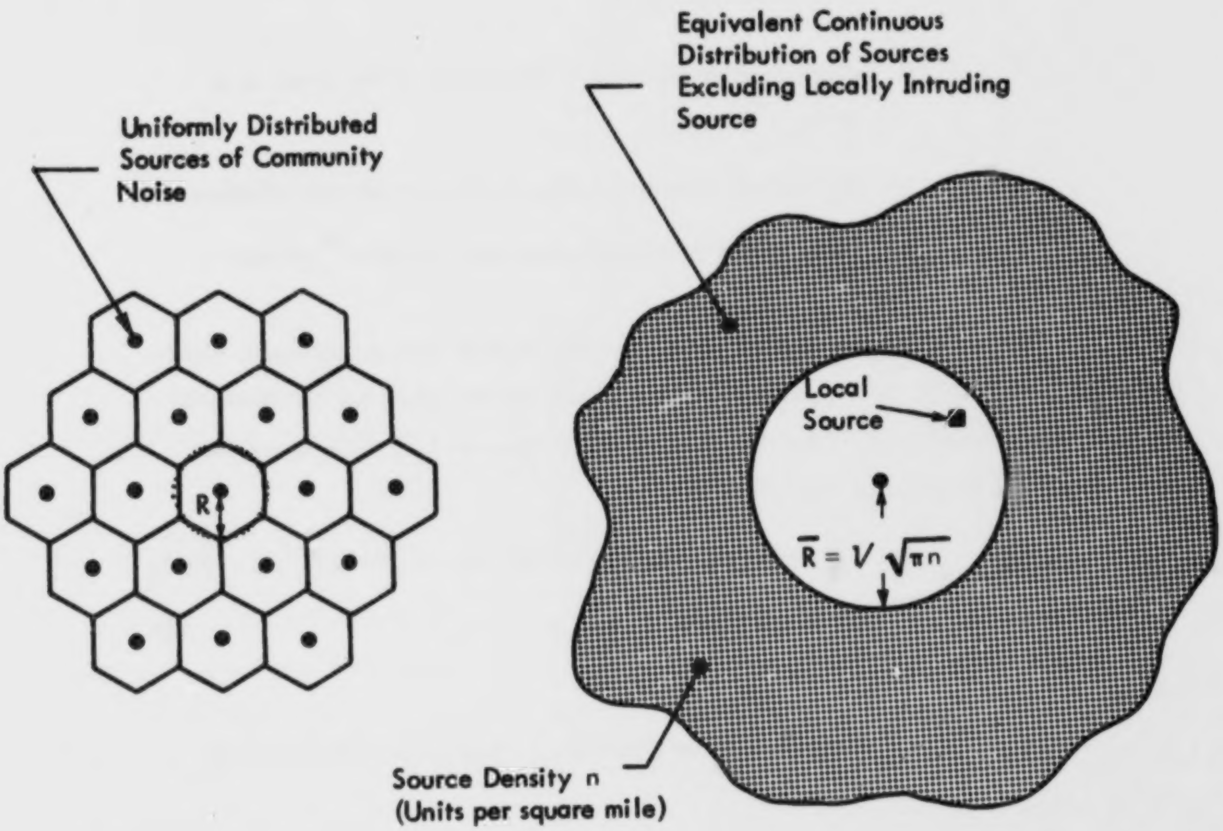

Uniformly Distributed Sources of Community Noise
R
Equivalent Continuous Distribution of Sources Excluding Locally Intruding Source
Local Source
$\overline{R} = 1/\sqrt{\pi n}$
Source Density n (Units per square mile)

Figure B-4. Model for Residual Noise Level (Excluding Local Source) in terms of the mean square pressure $\overline{P_R^2}$, is:[12]

$$\overline{P_R^2} = \sum_i^{\infty} \overline{P_o^2} \left(\frac{R_o}{R_i}\right)^2 e^{-m R_i} s_i \qquad (2)$$

where

$\overline{P_o^2}$ = mean square reference pressure of each source at the reference distance R_o

R_i = distance from observer at the center of the local zone to the i^{th} source

m = the excess attenuation loss coefficient per unit distance

s_i = local shielding loss between observer and i^{th} source.

By replacing the distribution of discrete sources with a continuous distribution and integrating from the outer radius R of the "local zone" out to infinity to sum up the contribution of all but the local source to the residual noise level, one can express this level (L_{90}) in decibel form as

$$L_{90} = L_A + 10 \log \left[E, (X)\right] + 10 \log n + 20 \log R_o - S - 66.5, \quad \text{dB re: } 20\ \mu N/m^2 \qquad (3)$$

where

L_A = Reference A-weighted noise level of each source at the R_o in feet

$$E, (X) = \int_{\overline{R}}^{\infty} \frac{e^{-mR}}{R}\, dR$$

the exponential integral of the first kind of argument X[13].

$x = m/\sqrt{\pi n} = 0.686\, a/\sqrt{n}$

a = attenuation loss coefficient in dB/1000 feet

n = density of sources per square mile

S = average shielding loss between observer and surrounding noise sources, dB.

The relationship predicted by this expression for the residual noise level relative to the reference noise level L_A of a source at a distance of 50 feet is shown in Figure B-5 for a range of values of the excess attenuation coefficient and zero shielding loss. A typical minimum value of excess attenuation rate, due to air absorption only, for ground transportation sources is about 1 - 2 dB per 1000 feet.[14, 15] These are approximate values for the effective attenuation rate when applied to the overall A-weighted noise level and are based on recently revised models for air absorption.[16,17,18] These are considered more accurate for predicting losses at low frequencies than earlier prediction methods.[19,20] The additional shielding loss due to diffraction or reflection by buildings between the sources and the observer has been found to be about 6 dB.[21,22] Substantially higher values of shielding loss (10 - 15 dB) have been reported from horizontal propagation tests of warning sirens over communities; however, these higher values do not appear to be entirely applicable for predicting shielding loss of traffic noise.[23]

The source density n is estimated by the product:

$$n = P \cdot r \cdot F \cdot T/24$$

Where P is the population density, r is the number of sources per person, F is the fractional usage in the type of community being considered, and T is the number of operating hours per 24-hour day. The primary objective in applying this model is to illustrate the approximate contribution to the residual noise level by transportation sources. Average values for these parameters were chosen, therefore, to represent the source density and usage in a typical urban community. On this basis, the average urban population density for 1970 was assumed to be 5000 persons per

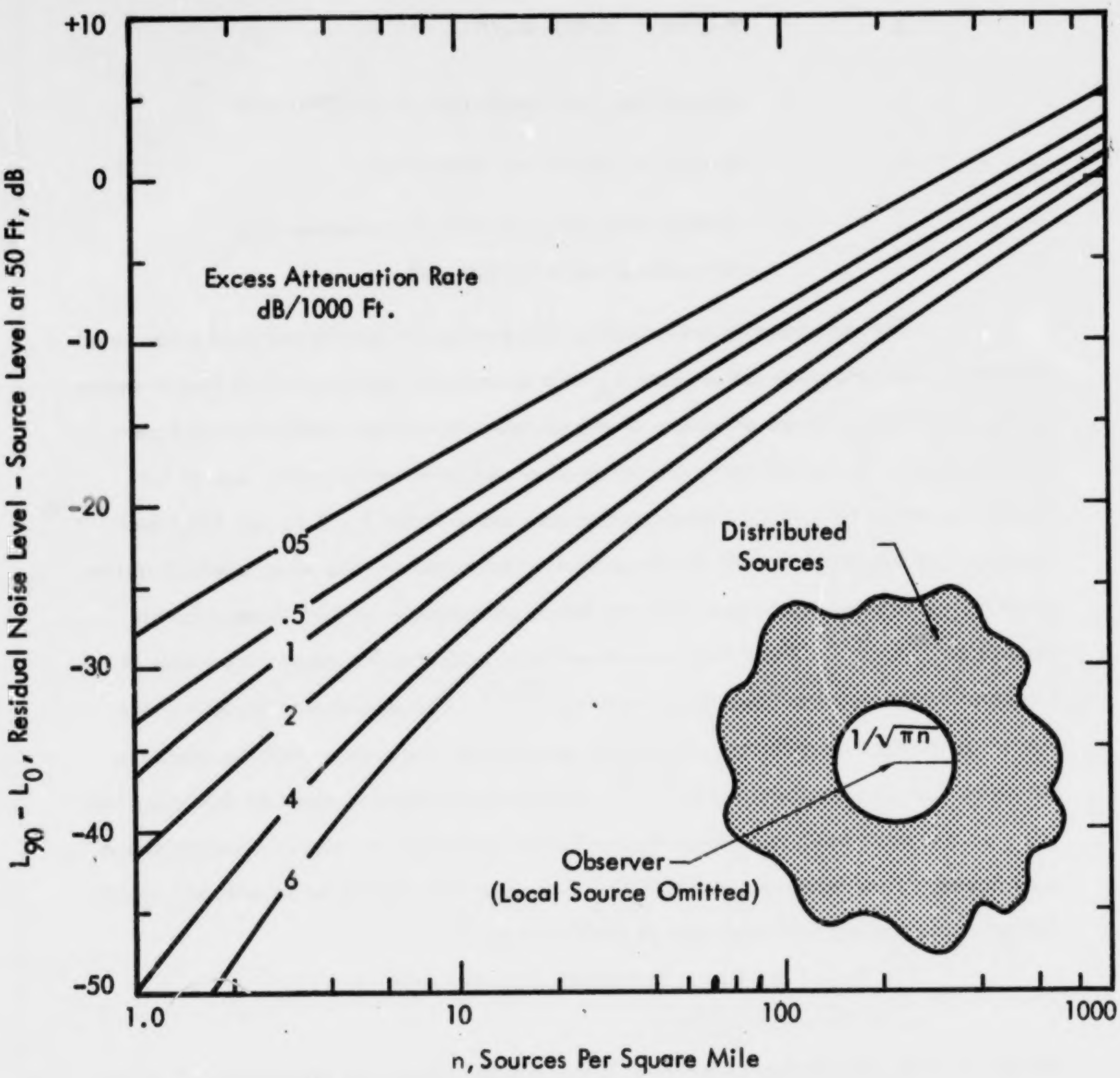


Figure B-5. Residual Noise Level Relative to Source Noise Level at 50 Feet Without Shielding Loss (Adopted from Reference 12) square mile.[1] While there has been a progressive decrease in the average population density of urbanized areas over the last 20 to 30 years due to urban sprawl, the rate of this decrease is slowing down and is being counteracted by the growth of apartment dwellings in close-in areas.[1,24] Thus, for purposes of projection of noise impact in the future, it was considered reasonable to assume that the average urban population density remained constant. The number of sources per person was assumed equal to the total number operating in the nation, divided by the total population (see Table B-2 and Figure B-3). Only sources operating on roads and highways were considered for estimating ambient levels. Normally, the other transportation sources do not contribute significantly to the urban residual noise environments. Estimates of the fractional usage in an urban community and operating time for each source were made on the basis of available information on urban highway usage. The resulting estimates of the usage and density of operating sources per square mile for the years 1970, 1985 and 2000 are summarized in Table B-3. Note that the projected increase in source density from 1985 to the year 2000 is slight due to the assumed trend of number of sources per capita approaching a constant by the year 2000.

The estimated trends in the daytime residual noise level in a typical urban residential area, based on this model, have been shown in Figure 4-1 in Chapter 4. For 1970 conditions, the three most significant contributing sources for this residual noise level are:

• Passenger Cars (All Types)	45 dB(A)
• Light Trucks and Pickups	42 dB(A)
• Heavy and Medium Trucks	33 dB(A)
Total	47 dB(A)

During nighttime the contribution by passenger cars and light trucks will decrease substantially, but the contribution by heavy trucks tends to remain nearly constant. This is illustrated by Figure B-6 which shows the hourly and daily traffic flow rates on intercity highways in California.[25] Since this intercity travel normally involves travel on urban freeways, the contribution by trucks to the residual noise

Table B-3

Summary of Estimates of Density of Operating Highway Vehicles in Urban Residential Areas from 1970–2000

Source	Fractional Use in Urban[1] Areas	Operating Time Hours Per Day	Operating Source Density[2] Units/Square Mile		
			1970	1985	2000
Passenger Cars (Standard)	80	1	50	62	65
Sports, Compact and Import Cars	80	1	20	26	30
Light Trucks and Pick-ups	60	1.5	20	23	25
Medium and Heavy Duty Trucks	10	4	1.5	1.8	2.0
Motorcycles (Highway)	80	1	1	2.3	2.5
City Buses	100	2	0.8	0.7	0.6

[1] Use in urban residential communities.

[2] Assuming constant population density at 5000 people/square mile.

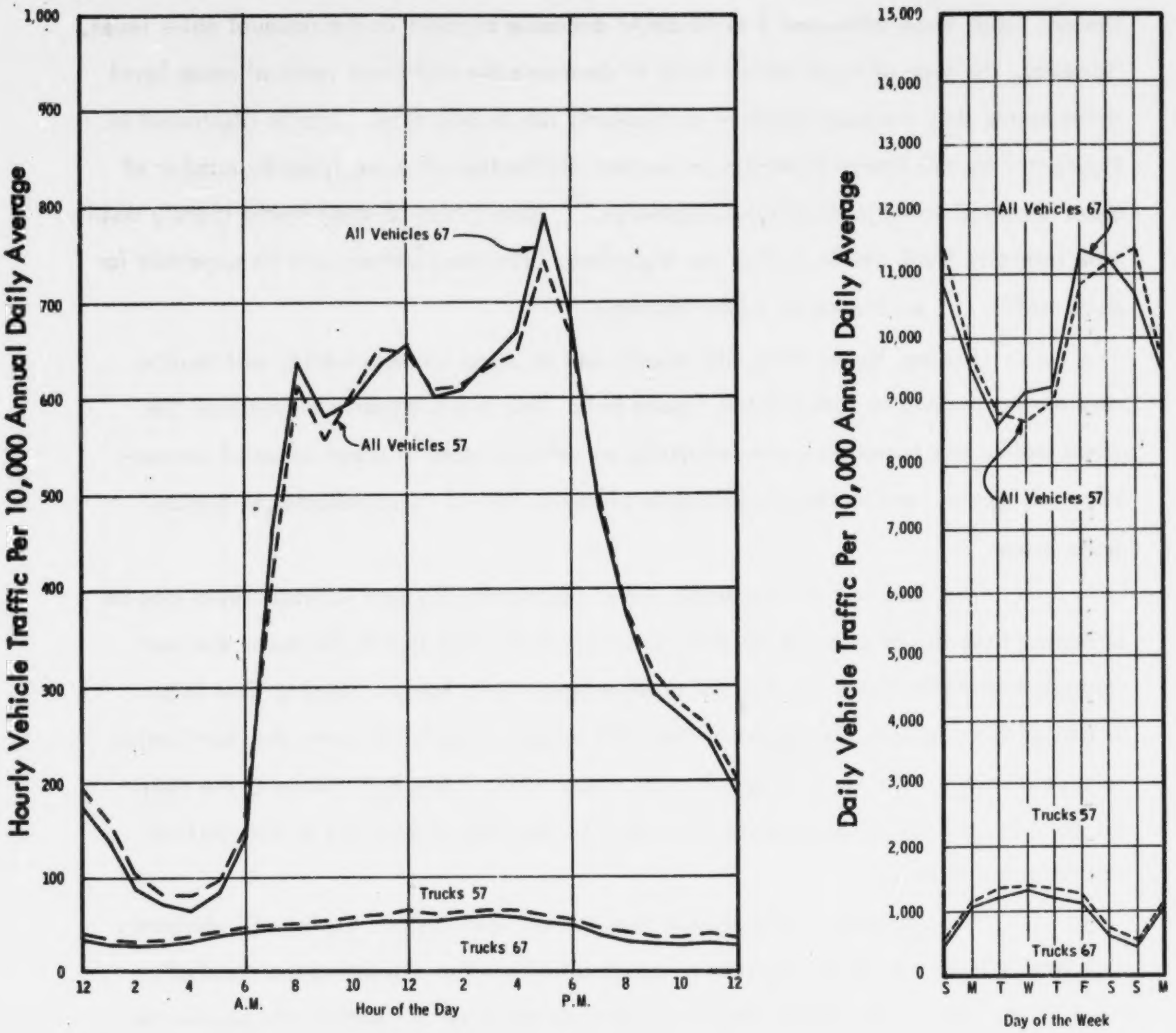


Figure B-6. Hourly and Daily Variations in Intercity Highway Traffic on Major California Intercity Highways. Expressed in Terms of Vehicles Per 10,000 Annual Average Daily Traffic.
Data Shown for 1957 and 1967. (From Reference 25)

level does not vary as much during a 24-hour period as the contribution from automobiles. The net result is an estimated 5 to 10 dB(A) decrease at night in the residual noise level. However, the type of truck which tends to dominate the nighttime residual noise level is the heavy duty transport truck — particularly the 5-axle type. This is illustrated in Figure B-7 by the hourly variation in percent distribution of truck types by number of axles observed on major California highways.[25] Heavy-duty 5-axle trucks clearly dominate intercity truck traffic during the nighttime. The same pattern can be expected for truck traffic mix on the major urban freeways.

During the daytime, the hourly mix of urban vehicle traffic will tend to vary during the day as indicated in Figure B-8. This is a composite estimate of the urban traffic mix based on known statistics on vehicle miles in urban areas of automobiles and trucks, and on detailed samples of hourly mix of these vehicles in typical urban areas.[2,9]

The detailed mix for truck traffic during the daytime in urban areas can be estimated from the data in Tables B-4, B-5, and B-6. The first table shows the percentage distribution by truck size for three ranges of trip lengths ranging from local (urban or farm) to long haul (greater than 200 miles). Table B-5 shows the distribution by type of trip for the same range of truck sizes, while Table B-6 indicates the distribution of truck trips in urban areas according to the type of land use at the starting and termination points.

The variation in population density and vehicles per capita will obviously vary from city to city from the typical values used here for estimating the residual noise level. Figure B-9 illustrates the general distribution of central city population density according to 1960 census data for the 128 largest cities in the United States.[1,9] This shows two general trends in population density. It is generally higher for cities with a higher total population and, as indicated by the four lines characterizing regional areas, is higher for older regions. This is simply reflecting the fact that the population of a geographically fixed urban land area tends to increase gradually with time. Automobile and truck ownership, on the other hand, tends to decrease with

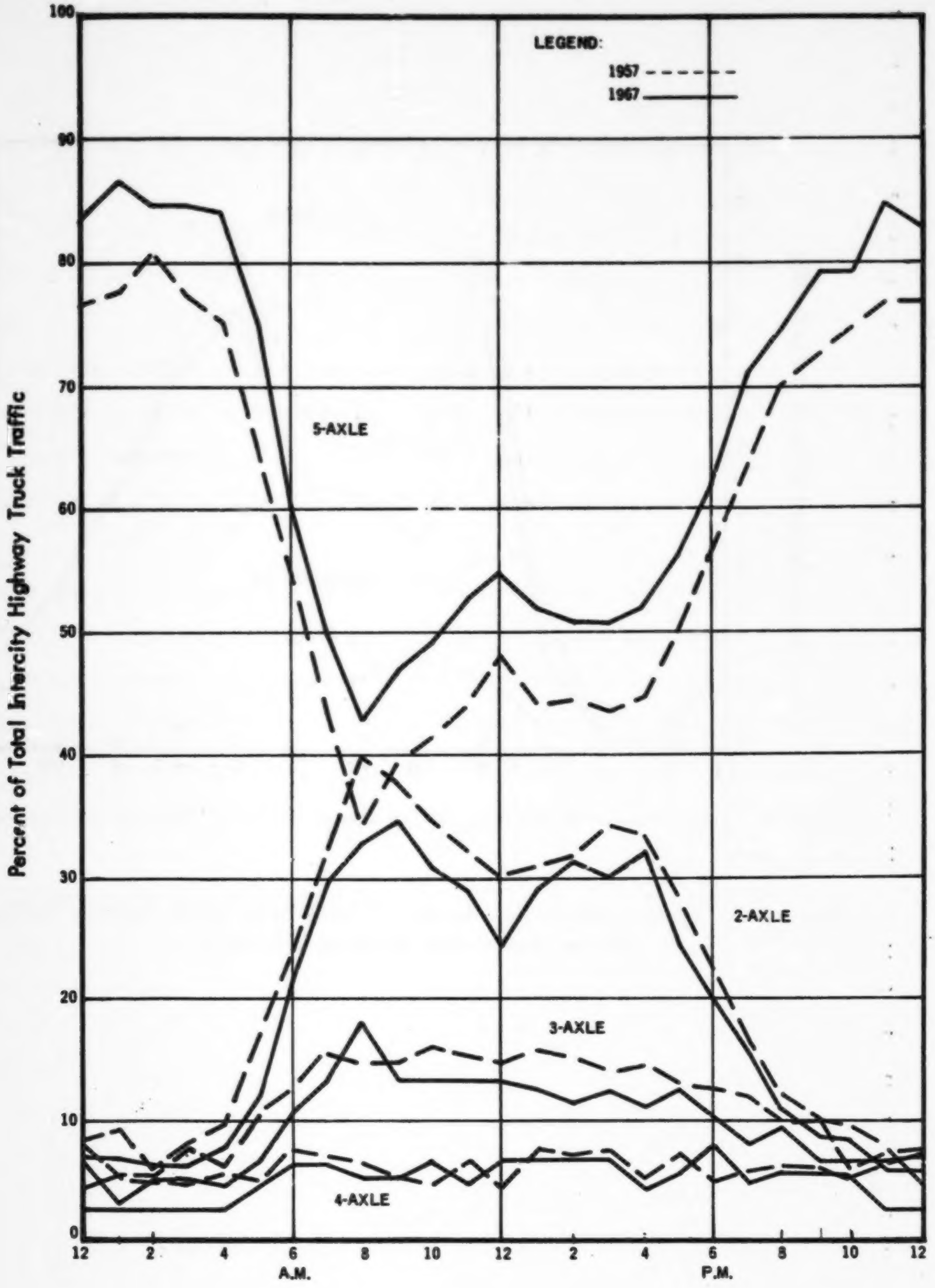


Figure B-7. Hourly Variation in Mix of Truck Traffic Observed in Major Intercity Highways in California
(From Reference 25)

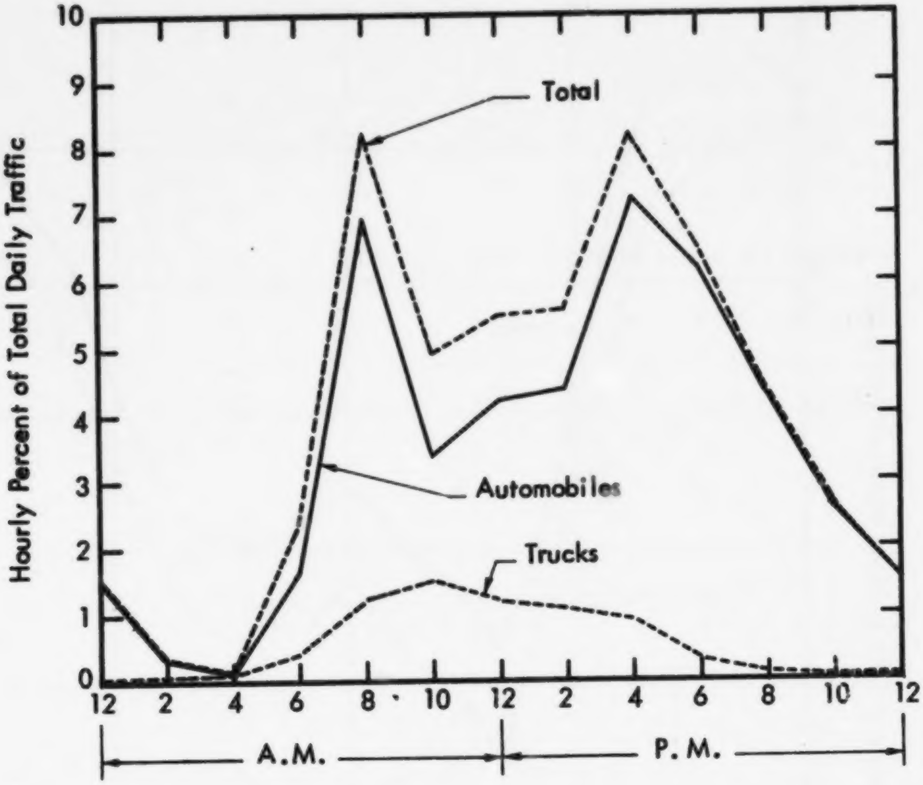


Figure B-8. Typical Hourly Distribution of Total Daily Urban Vehicle Traffic
(Based on data from References 2 and 9)

Table B-4

Distribution of Annual Truck Vehicle-Miles According to Truck Size and Type of Trip (From Reference 9)

Type of Trip	Percent by Truck Type (Gross Weight) <10,000 Pounds	10-26,000 Pounds	>26,000 Pounds	Miscellaneous	Total
Local (Urban or Farm)	66.8	21.2	7.0	5.0	100%
Intermediate (<200 miles)	27.8	20.8	42.7	8.7	100%
Long Haul (>200 miles)	5.9	4.3	79.0	10.8	100%
Total – All Trips	54.5	18.4	20.9	6.2	100%

Table B-5

Distribution of Type of Truck Travel According to Truck Size (From Reference 9)

Type of Trip	Truck Size (Gross Weight) <10,000 Pounds	10-26,000 Pounds	>26,000 Pounds	Total All Trucks
Local	87.7	75.1	21.4	68
Intermediate	11.1	22.6	40.0	21
Long Haul	1.2	2.3	39.0	11
Total	100%	100%	100%	100%

Table B-6

Distribution of Truck Trips by Urban Land Use at Start and End of Trip
(From Reference 9)

From \ To	Residential	Non-Residential	Total
Residential	24.1	16.8	40.9
Non-Residential	18.0	41.1	59.1
Total	42.1	57.9	100%

population or population density as indicated in Figures B-10 and B-11 respectively. This is a reflection of the greater use of urban mass transit in crowded older cities. The net effect on predictions of residual noise level in urban areas will be a trend to make the density of highway vehicle sources more nearly constant and roughly independent of city size.

Finally, as an indication of the sensitivity of the residual noise level to changes in the input parameters, the effect of changes in the estimated density of the operating sources is illustrated by the following alternate cases:

	Change in Residual Noise Level dB(A)
• Increase density of heavy trucks by factor of 4	+2
• Increase passenger car density by factor of 2	+4
• Increase density of all sources by factor of 2	+5
• Increase passenger car density by factor of 4	+8

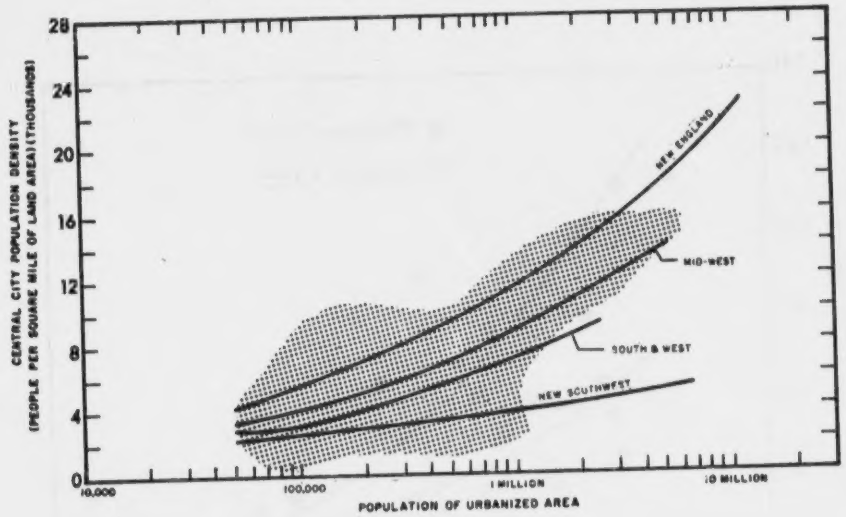


Figure B-9. Central City Population Density as Related to Urbanized Area Population
(From Reference 1, 9)

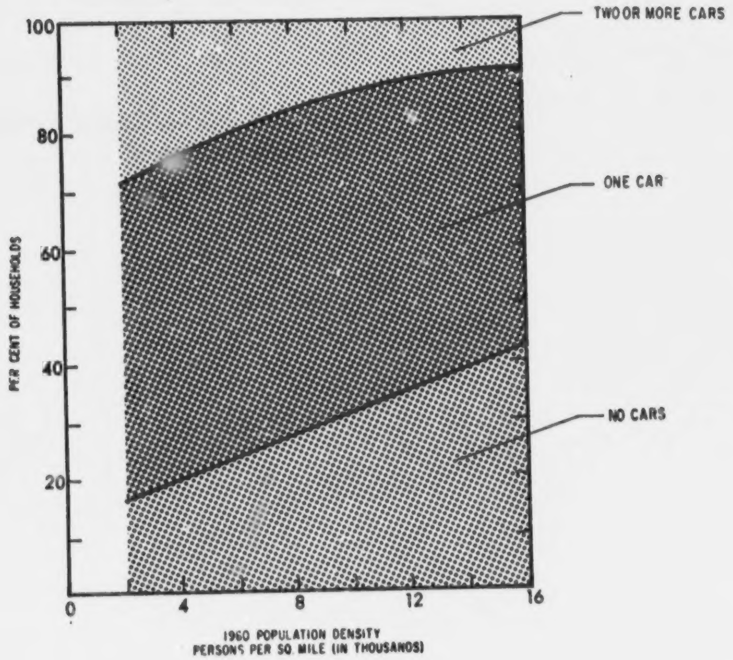


Figure B-10. Effect of Central City Population Density on Automobile Availability
(From Reference 9)

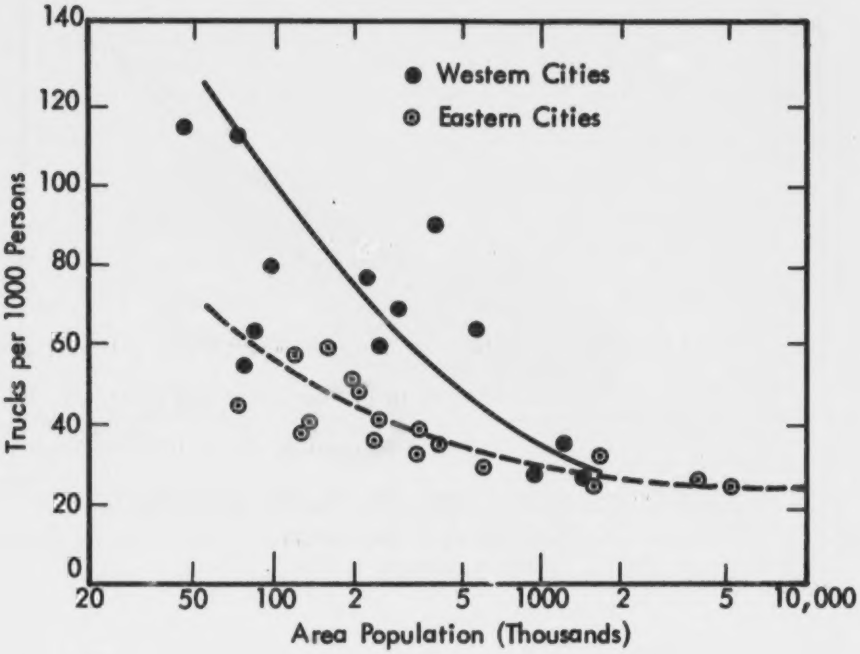


Figure B-11. Registered Trucks/Capita, 1963-65
(From Reference 9)

B.3 Single Event Noise Levels for Major Transportation Noise Sources as a Function of Distance

The evaluation of relative annoyance of single events, presented in Section 4.3, required prediction of single event noise levels as a function of distance from the source. This was carried for both measures of single event levels utilized as follows:

Maximum A-Weighted Noise Level*

The reference octave band spectrum for each source of a fixed distance (50 feet for surface vehicles – 1000 feet for aircraft) was used as a baseline for predicting the decrease in octave band levels at greater distances using atmospheric absorption loss coefficients and ground absorption loss values from References 14 and 15. The attenuated levels at octave band were then recombined after applying the A-weighting convection to the spectrum to define the new A-weighted noise levels. Typical results of this process are illustrated in Figure B-12.

Single Event Noise Exposure Level (SENEL)*

The SENEL for a single event can be expressed as the sum of its maximum noise level and an effective duration correction factor. The effective duration of noise for moving sources is a function of the distance from the source (R) and its velocity (V). For surface vehicles such as automobiles and trucks, the SENEL can be roughly approximated as follows:

$$\text{SENEL} \simeq L_A(R) + 10 \log\left[\frac{\pi}{2}\,\frac{R}{V}\right], \text{ dB re } 20\ \mu\text{N/m}^2 \text{ and 1 second} \qquad (4)$$

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*See glossary of terms at end of this Appendix for definition.

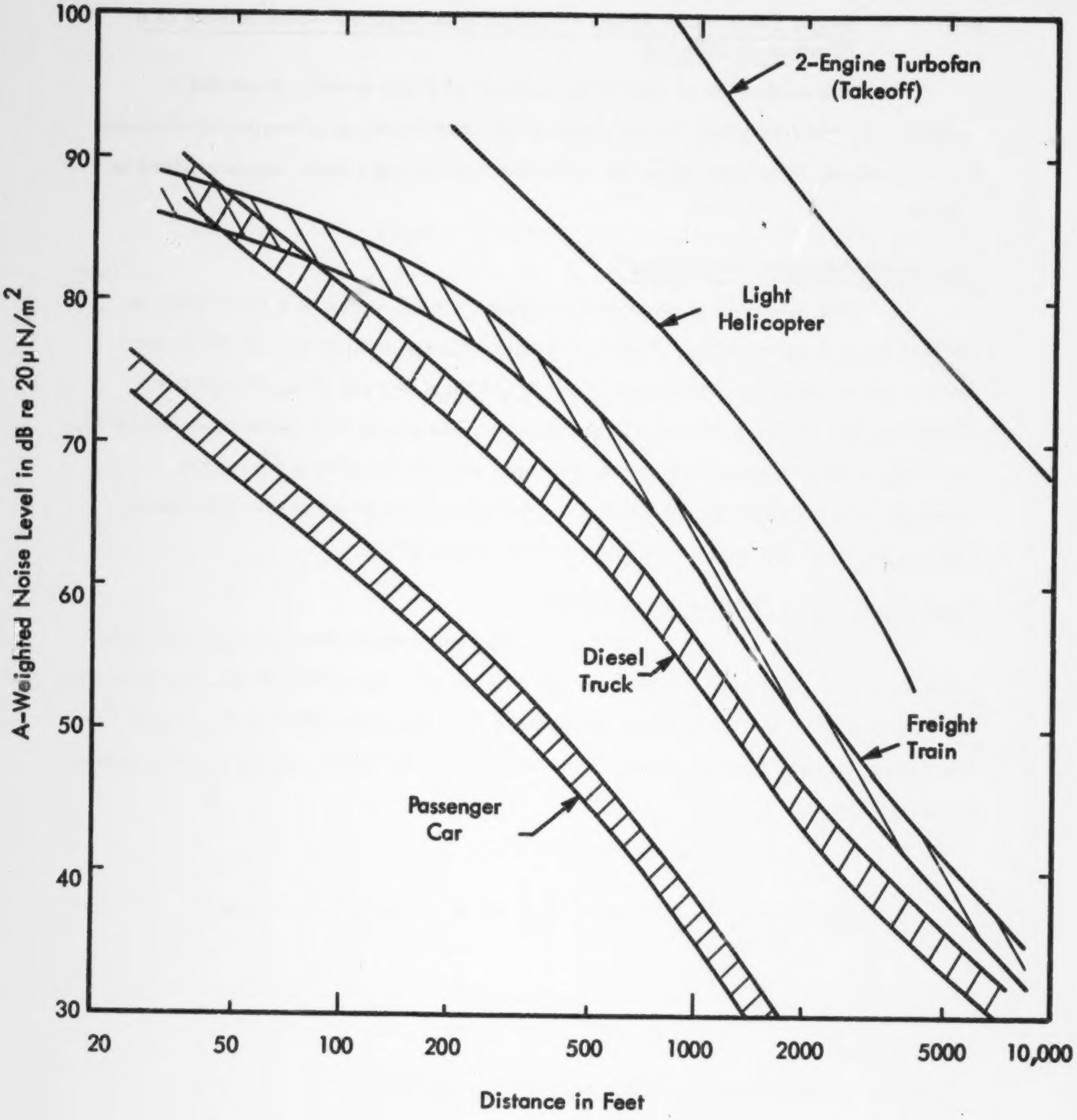

Figure B-12. Variation in Typical Noise Levels vs Distance For Several Transportation System Categories

where

$L_A(R)$ = A-weighted noise level at the distance R
R = Distance in feet
V = Speed of the vehicle in ft/sec

For trains, the duration of the passby noise is essentially equal to the passby duration (train length/speed) within a distance R equal to L/π where L is the train length. Thus, within this range, the second term in Equation (4) is replaced with 10 log L/V . At greater distances, Equation (4) is used since the long train (line) source begins to act like a point source at these distances.

For aircraft, SENEL values were predicted in the same manner used for predicting Effective Perceived Noise Levels (EPNL) as a function of slant distance to the aircraft.[26,27,28] The latter time-integrated measures of single-event noise are used for evaluating noise impact near airports due to aircraft operations.

B.4 Noise Impacted Land Areas Around Freeways and Airports

As indicated above, the methodology for evaluating noise impact near airports is well developed and fully documented by examples such as in Reference 29. The index used for evaluating the noise impact is the noise exposure forecast (NEF) which is a measure of the composite time-integrated noise exposure on the ground due to aircraft operations. The evaluation of noise impacted land area for the total transportation system dictated the need to apply a similar methodology to highways. The index of noise impact utilized in this case is the community noise equivalent level (CNEL). This composite measure of noise, defined in the Glossary at the end of this Appendix, utilizes A-weighted noise levels as a basic measure of noise magnitude.

As for the NEF scale, a CNEL value accounts for the time-integrated single-event noise level (expressed by an SENEL), the number of single events in a 24-hour day and, by weighting factors, the time of day in which these single events occur. These weightings approximate the increased sensitivity of a community to intrusive noise during the evening and nighttime periods.[27] This composite scale can be used in the same way as the NEF scale to predict reaction of a community to an accumulation of intrusive noises.[11] The CNEL value at a given point can be approximated by:

$$\text{CNEL} \simeq \overline{\text{SENEL}} + 10 \log N_F - 49.4 \text{ dB} \qquad (5)$$

where

$\overline{\text{SENEL}}$ = average SENEL for each single event

N_F = weighted number of single events equal to $N_D + 3 N_E + 10 N_N$

N_D, N_E, N_N = number of single events during the daytime (7:00 a.m. - 7:00 p.m.), evening (7:00 p.m. - 10:00 p.m.), and nighttime (10:00 p.m. - 7:00 a.m.), respectively.

For analysis of the CNEL near freeways, an average SENEL is selected for each type of vehicle, using Equation (4), along with corresponding figures for the number of vehicles passing by during each of the three time periods. The total CNEL for this traffic mix is the logarithmic (or energy) summation of the CNEL values for each type of vehicle. Typical SENEL values for each type of highway vehicle at a reference distance of 50 feet have been specified in Table 4-6 of Chapter 4. The SENEL at other distances was computed in the manner explained in Section B.3.

Close to a freeway, the propagation loss for the maximum noise level decreases according to the inverse square law of distance R from the source (i.e., $\sim 1/R^2$). However, the time-integrated measure of the single event (SENEL) includes a correction for duration which increases directly as the distance R. The net result is that the SENEL decreases according to a first power law with distance from the vehicle.

This is exactly equivalent to other analytical models for predicting noise near highways, which show that for high traffic volumes (roughly greater than 1000 vehicles per hour), where the traffic noise can be treated as a line source, the average noise level near the freeway decreases according to the first power of the distance from the traffic lane.[30,31] The average A-weighted noise levels (L_{50}) predicted by these latter models, for a wide range of traffic volumes and average vehicle speeds, are shown in Figure B-13. In this figure, the change in slope of the curves with traffic flow rate is due to the change in character of the noise as traffic volume increases. For low flow rates, each vehicle is heard as an isolated single event as it passes by. For high flow rates, the stream of traffic is heard as a nearly continuous quasi-steady state noise with only minor fluctuations due to the particular traffic mix at any instant.

For evaluation of noise impact on all types of urban roads, the following additional parameters were required beyond those already described:

- Mileage on each type of road
- Typical vehicle speed by road type
- Typical traffic flow rates
- Typical road right-of-way

These parameters are defined in Table B-7 for 1970 road conditions.

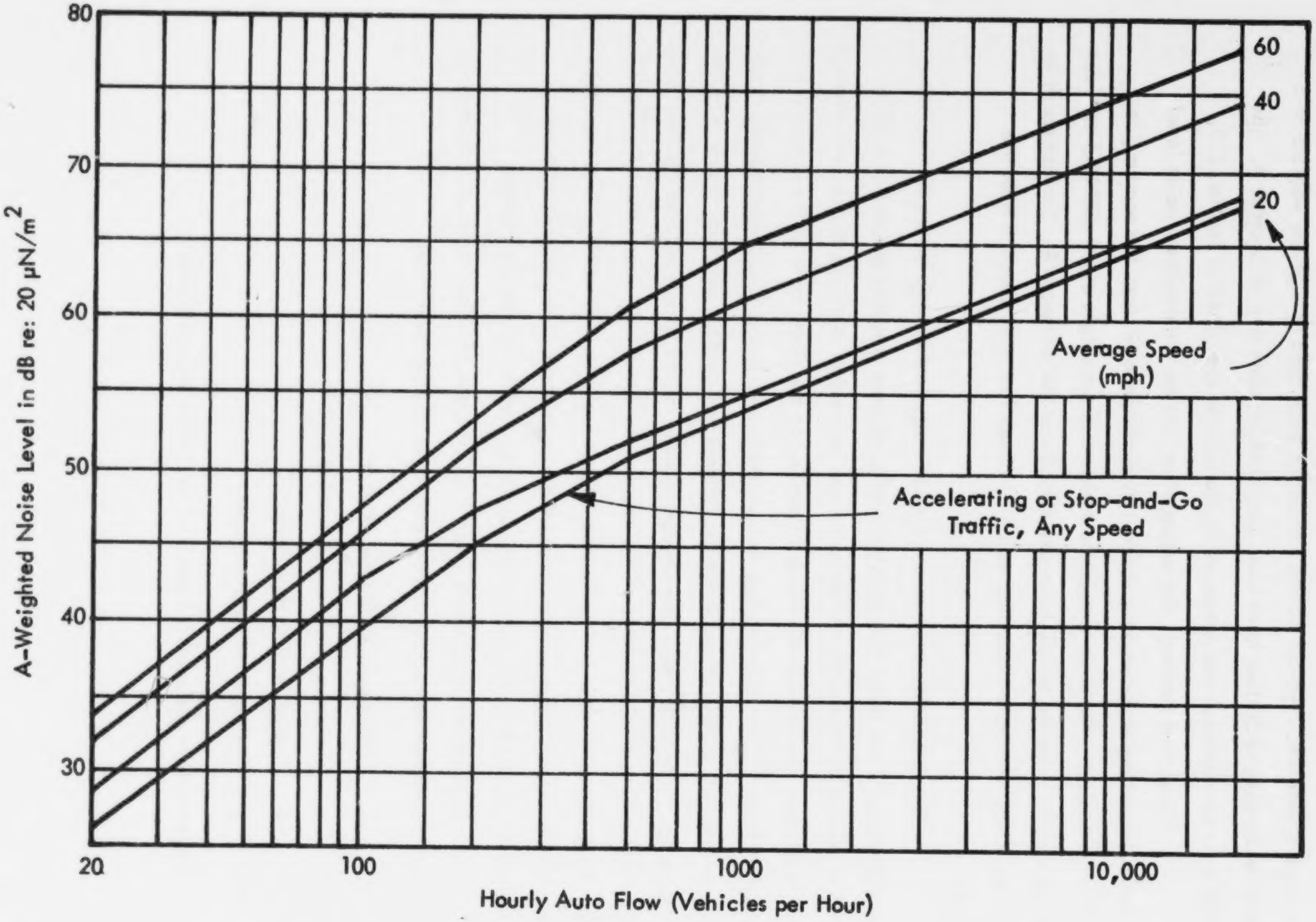

Figure B-13. Typical Noise Levels for Automobiles at 100 Feet from Highway[31]

Table B-7

Highway Mileage and Estimated Average Highway Speeds for Urban Areas in 1970

	Mileage[1] Miles	Typical[2] Speed mph	Typical[3] Flow Rates Vehicles/Hr	Typical[4] Right-of-Way (No. of Lanes) Feet
Freeway	9,160	55	1,980	200 (8)
Major Arterial	38,535	40	735	175 (6)
Minor Arterial	46,991	40	365	160 (5)
Collector	43,970	30	157	150 (4)
Local	351,300	25	43	125 (2)

Notes

1 For urban areas in 1968 from Reference 32.

2 Estimated based on typical free traffic flow.

3 Computed average (see text).

4 Estimated effective value based on 12 feet per lane and 50-foot setback to nearest residence from edge of roadway.

Effect of Vehicle Speed

Varying the average vehicle speed has two effects. The average maximum noise level for most highway vehicles increases approximately according to the cube of the vehicle speed.[31,33,34] Although noise levels of heavy (diesel) trucks increases less with speed, due to their small contribution to the total highway noise impact, the cube rule for vehicle speed was assumed for all vehicles.

The second influence of vehicle speed is that it changes duration of a single event and hence the SENEL, as indicated by Equation (4). The net result is that the average SENEL for each type of vehicle varies by the square of the vehicle speed, as indicated by the following correction factor:

$$\Delta S = 20 \log \frac{V(\mathrm{mph})}{40}, \ \mathrm{dB} \tag{6}$$

Forty (40) mph is used as the nominal reference speed corresponding to the reference SENEL at 50 feet for each type of vehicle.

Effect of Traffic Flow Rates

The average traffic flow rates Q listed in Table B-7 for each road type were based on an average value computed by:

$$Q = \frac{\text{Vehicle - Miles per day}}{(17\text{ hours}) \times (\text{Road Mileage})}, \ \text{vehicles/hr}$$

This provides a highly smoothed average flow rate based on total national figures for traffic volume, road mileage, and an average "traffic day" of 17 hours.[32] (See Figure B-8.) Actual flow rates on many urban freeways will be substantially greater than this. However, to counterbalance this unconservative assumption, it was assumed, when evaluating the noise impacted area near freeways, that the entire length of the freeway was adjacent to residential land.

The weighted number of single events N_F required for computation of the CNEL was substantially greater than the actual daily total. Using typical hourly rates of urban traffic, such as indicated in Figure B-8, and the weighting factors for time of day indicated for Equation (5), the weighted total number of events (vehicles) was 2.2 to 3 times the actual daily total. For conservatism, a factor of 3 times the daily total was used for this analysis.

Additional Factors for Freeway Impact Analysis

An average shielding loss of 3 dB was used to approximately account for the attenuation effect of barriers at the edge of freeways. In fact, freeway noise can be changed substantially (up to 10 to 15 dB), depending on the design of barriers and elevation of the road.[31,35] The value of 3 dB was considered a reasonable average for the wide range of freeway design conditions that exist.

No attempt is made to account for the effect of changes in road grade or conditions of the road surface on traffic noise. Both of these factors can be significant in specific situations.[31]

The effect of varying distances from an observer to each lane of traffic on a multi-lane highway with two-way traffic was accounted for by a single correction factor to allow computations of noise impact to be based on an equivalent single-lane flow of traffic.

The nearest residence to all highways was assumed to be 50 feet from the edge of the roadway. The width of the roadway itself was assumed to be 12 feet for each lane, with an average number of lanes varying with road type (as indicated in Table B-7). Thus, effective right-of-way was equal to the road width plus a 50-foot set-back on each side.

Noise Impacted Land Area

As discussed in Section 4.4 of the text, a criterion value of CNEL = 65 was selected as the outer boundary of the noise impacted area. The area involved for e each type of road was equal to:

$$A = 2 \left[d - d_R \right] \cdot L/5280, \text{ sq. mi.} \qquad (7)$$

where

d = distance in feet from "equivalent single lane" of traffic to position of CNEL = 65 contour

d_R = distance in feet from this lane (positioned at center of traffic flow closest to observer) to the edge of the effective right-of-way

L = total mileage for this type of road, miles.

The resulting predictions of noise impacted land area for highways in 1970 has been presented in Section 4.4 of the main text. For a criterion value of CNEL = 65, it was found that only freeways contributed to the estimated noise impact area. As discussed in Section 4.4, a lower CNEL criterion would be appropriate in some areas which have a lower residual noise level. However, since all land adjacent to the freeways was assumed to be residential, the noise impacted areas estimated are considered reasonable for ranking the relative contribution of freeways to noise impacted land of the transportation system.

Future Programs

The growth of freeway mileage has been very rapid over the past 20 years. However, the growth has slowed down to a current rate of about 5 to 7 percent per year. The initial rapid growth was responding to the urban expansion in the 1950's and the need for improved travel facilities. The marked effect of freeway development on urban travel efficiency is illustrated in Figure B-14. This shows the change in the 30-minute radius driving time in Los Angeles for three time periods – 1937, before freeways were available or urban growth had occurred; 1953, when there were only 45 miles of freeway in the city; and 1966, when the freeway system had expanded to about 340 miles.[36,37] The largest radius (shortest travel time) obviously occurs for the latter period, while the smallest radius (longest driving time) occurred in 1953 during the beginning phases of urban expansion.

Continued expansion of the freeway system in urban areas is expected to follow the trends indicated by Figures B-15 and B-16. The first shows the relationship between mileage per capita of various types of urban roads and city population.[32]

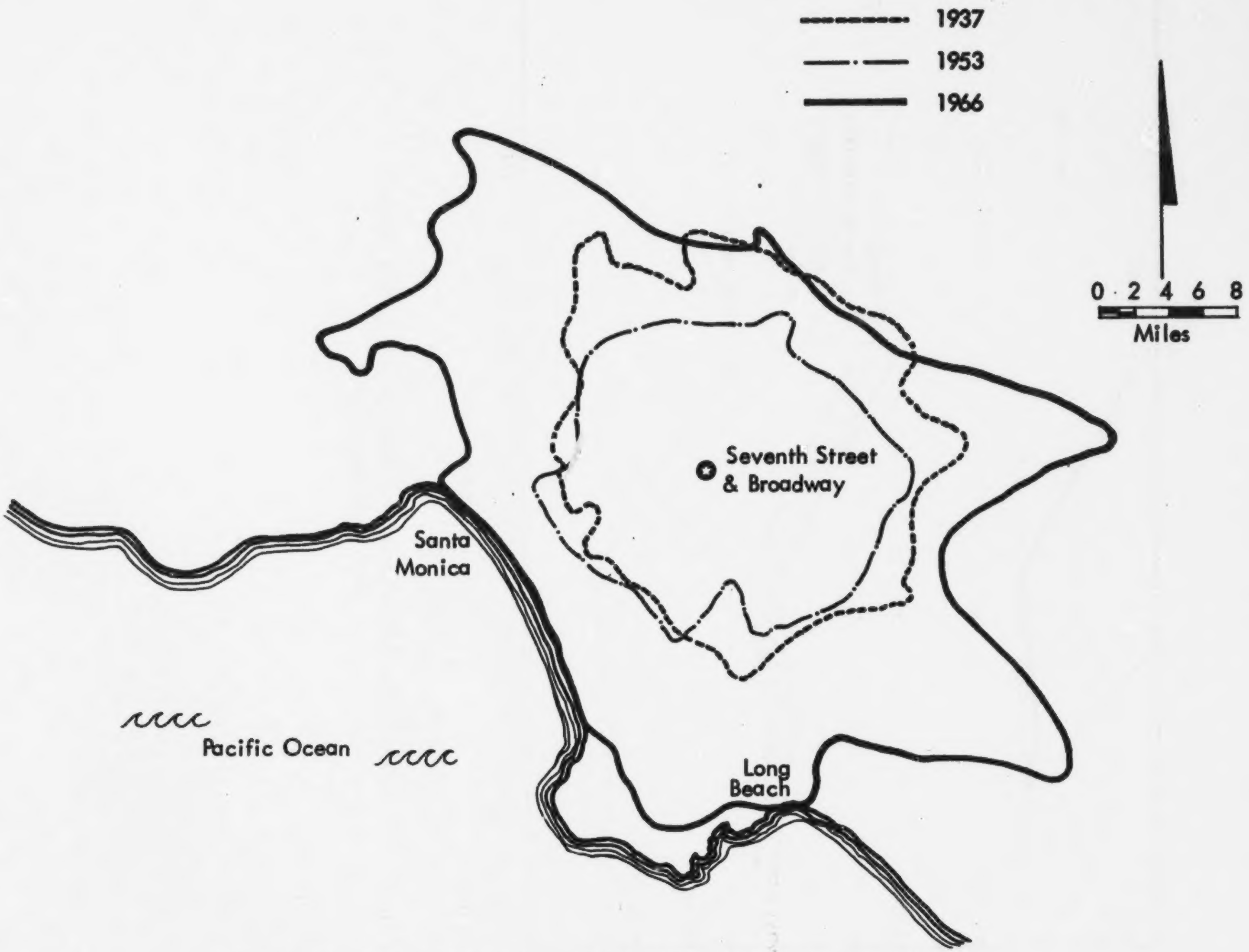
1937
1953
1966
0 · 2 4 6 8
Miles
Seventh Street & Broadway
Santa Monica
Long Beach
Pacific Ocean

Figure B-14. Radius of 30-Minute Driving Time to Downtown Los Angeles
(From Reference 36)

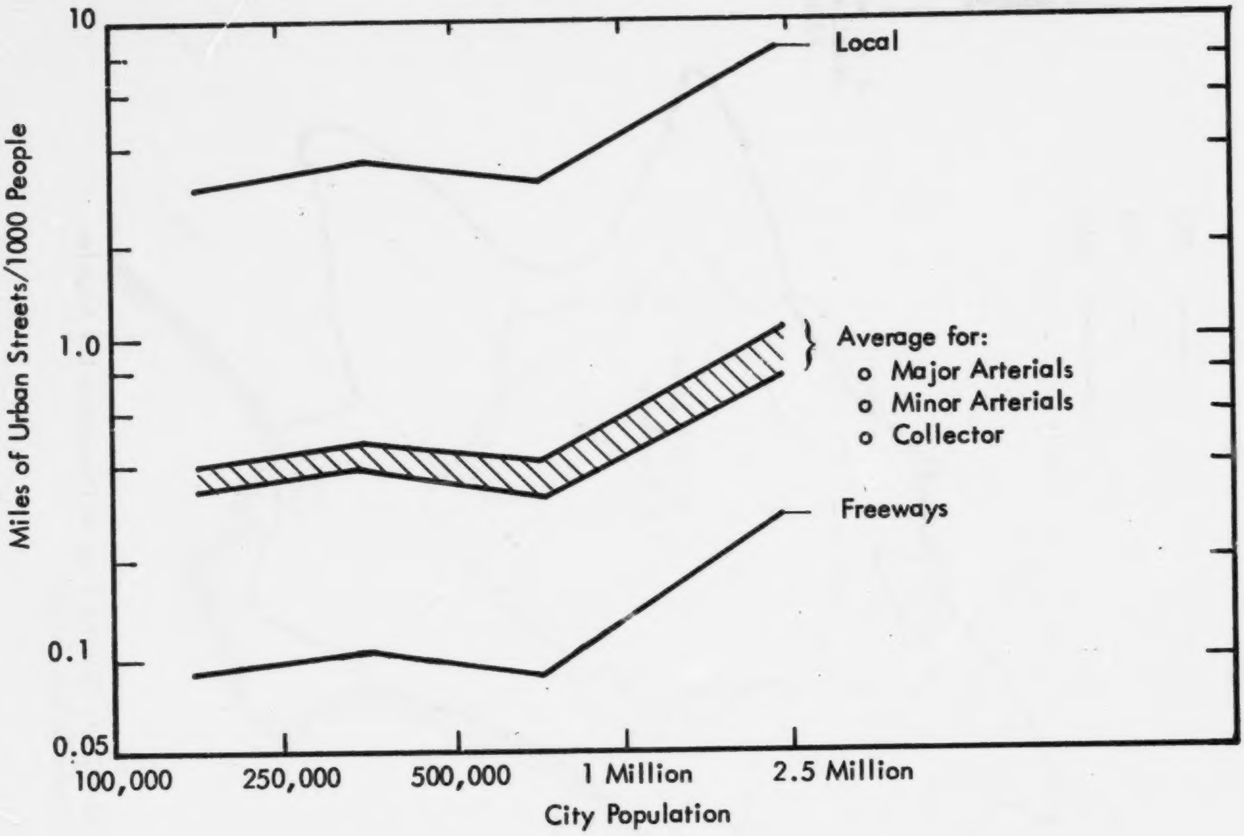

Figure B-15. Urban Street Mileage Versus City Population (From Reference 32)

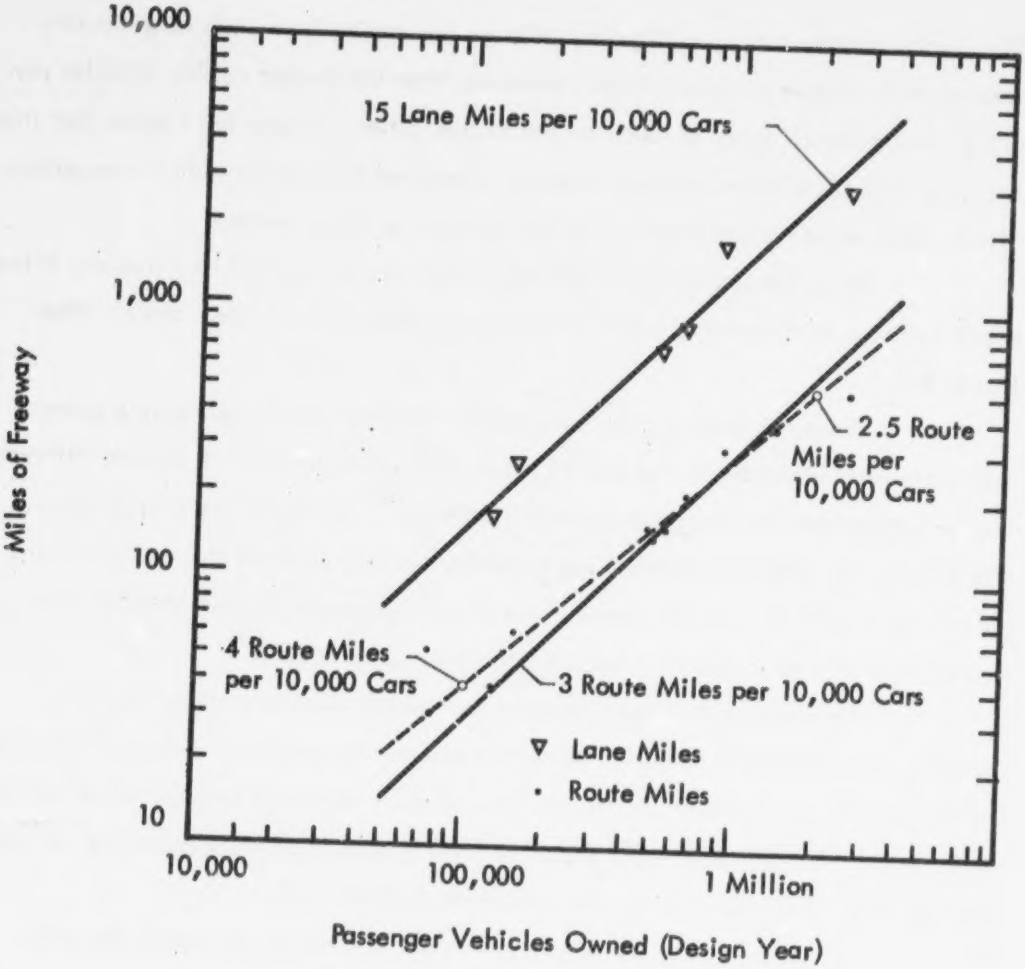

Figure B-16. Generalized Ranges in Urban Freeway Requirements in Relation to Passenger Car Ownership
(From Reference 8)

The nearly constant values of highway mileage per capita for a wide range in city population is clearly evident. Note, however, that the largest number of miles per capita occurs for all types of roads for the largest cities. Figure B-16 shows that there is a very high correlation between freeway mileage and passenger vehicle ownership, with a slight trend toward fewer miles per vehicle for larger cities.

Thus, for projection to the year 2000, it was assumed that freeway miles would increase in direct proportion to automobile ownership in urban areas. (See Figure B-3.)

There has been a small progressive increase in average vehicle speeds over main rural highways in the last 30 years, amounting to about 1 percent per year.[38] Engine horsepower has also progressively increased.[24] However, neither of these effects were considered in forecasting trends in highway noise in the future. There are, in fact, data to indicate that individual vehicles have become progressively quieter, which would tend to counteract the preceding effects.[34]

Considering that most freeway systems are currently operating near capacity, flow rates were assumed to remain essentially constant. Based on the preceding assumptions and methods, predictions of noise impacted land for urban highways for the years 1985 and 2000 were made for several options of noise reduction for highway vehicles. The results have been presented in Table 4-7.

Urban traffic on freeways is predicted to continue to create the only significant noise impacted land areas. This is due to the inherently high volume of traffic flow carried on freeways as compared to all other types of urban streets. As indicated in Figure B-17, even though freeways constitute only about 2 percent of the road mileage in a typical urban area, they handle 21 percent of the vehicle-miles — as much as all of the traffic on local streets.

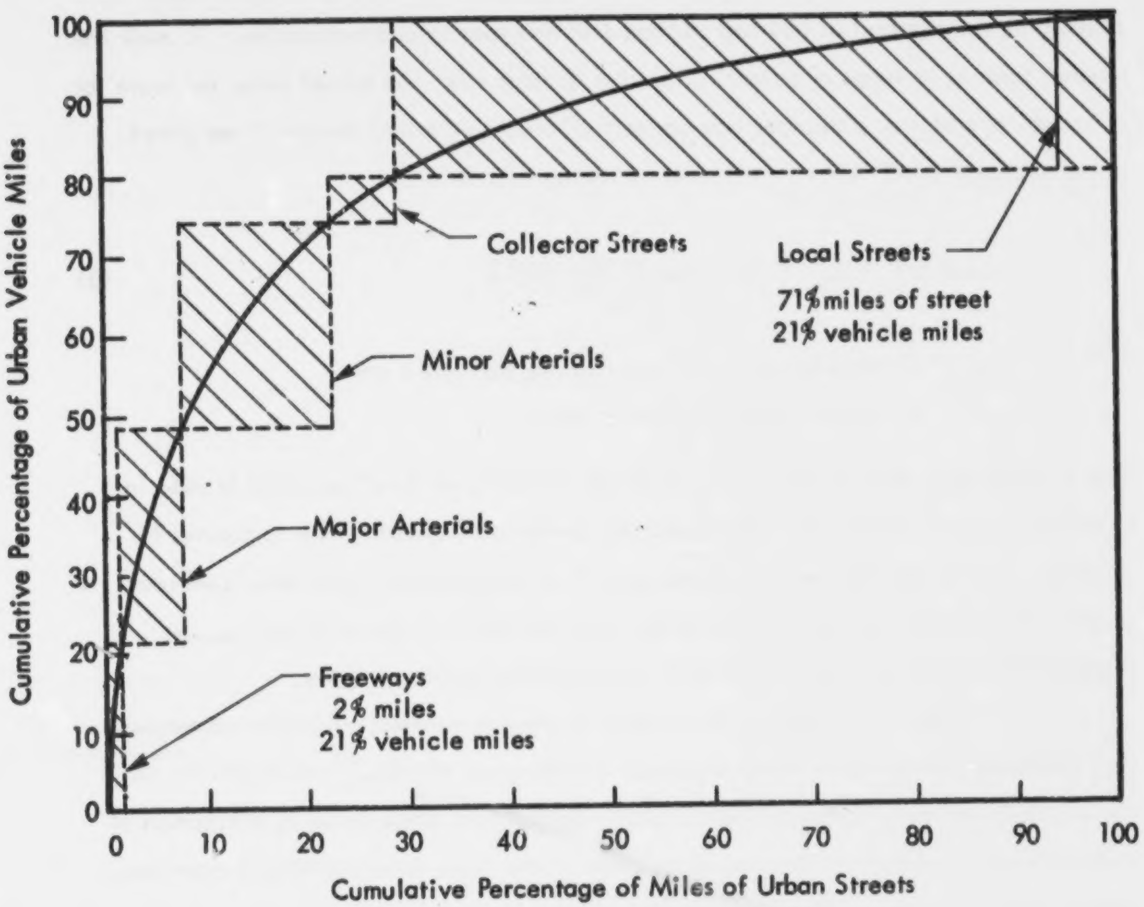

Figure B-17. Cumulative Urban Street Mileage Versus Cumulative Vehicle Miles Served in a Typical Urbanized Community[32]

B.5 Noise Impact on Operators or Passengers of Transportation Vehicles and Internal Combustion Engines

The two effects considered in evaluating noise impact on operators or passengers were potential hearing damage risk and speech communication. To rank the various sources in terms of potential hearing damage risk, the actual noise exposure for a typical operator or passenger was converted to an equivalent 8-hour A-weighted noise exposure level L(8 hr) with the following expression:

$$L(8\ \text{hr}) = L_A + 16.7 \log (T/8),\ \text{dB(A)} \tag{8}$$

where

L_A = A-weighted noise level at the operator's ear
T = typical exposure time in hours

This is essentially equivalent to the "5 dB per doubling of time" rule that is used in the Occupational Safety and Health Act for defining allowable noise exposures for employees. The equivalent 8-hour exposure levels estimated in this way have been presented in Figure 4-4 for transportation vehicles and in Table 4-9 for internal combustion engine devices, along with corresponding exposure times.

Impact of transportation systems on speech communication for passengers was evaluated primarily in terms of speech interference effects.[39] Criteria for the latter are specified in terms of the allowable background noise level as a function of talker-listener separation distance to prevent interference with significant continuous speech communication. The criteria allow for the tendency of a talker to raise his voice level as noise level increases above about 55 dB(A).

Conversely, the same criteria for negligible speech interference can also be used along with data on normal voice level to estimate the minimum levels desired in multi-passenger commercial vehicles to provide speech privacy. That is, a lower bound exists for the desired noise level in such passenger vehicles so that a private conversation cannot be overheard by adjacent passengers. This minimum internal noise level can be lowered only by decreasing talker-listener separation, or increasing the propagation loss between the talker-listener pair and an observer with a sound barrier. The criteria for speech privacy is based on maintaining an articulation index (AI) less than 0.05 for the undesired communication path.[40]

Table B-8 summarizes these two criteria for the major passenger vehicles and is based on the specified typical talker-listener separation distances. In general, most transportation vehicles meet these two criteria with the exception of multi-passenger helicopters, which are generally too noisy, and city or highway buses, which generally have internal levels lower than allowed for speech privacy between adjacent seats.

B.6 Glossary of Terminology

Sound Pressure Level (SPL)

The sound pressure level, in decibels (dB), of a sound is 20 times the logarithm to the base of 10 of the ratio of the pressure of this sound to the reference pressure. For the purpose of this report, the reference pressure shall be 20 micronewtons/square meter (2×10^{-4} microbar).

Noise Level (NL)

Noise level, in decibels, is an A-weighted sound pressure level as measured using the slow dynamic characteristic for sound level meters specified in ANSI S1.4-1971, American National Standard Specification for Sound Level Meters. The A-weighting characteristic modifies the frequency response of the measuring instrument to account approximately for the frequency characteristics of the human ear. The reference pressure is 20 micronewtons/square meter (2×10^{-4} microbar).

Single Event Noise Exposure Level (SENEL)

The single event noise exposure level, in decibels, is the level of the time-integrated A-weighted squared sound pressure during a given event based on referance pressure of 20 micronewtons per square meter and reference duration of one second.

Table B-8

Criterion Noise Levels for Speech Interference and Speech Privacy in Transportation Vehicles in Terms of A-Weighted Noise Levels

	Maximum for No Speech Interference		Minimum for Speech Privacy			
				Barrier Loss		
Vehicle	Talker-Listener Distance[2] Feet	dB(A)[1]	Observer Distance[3] Feet	0	5 dB	10 dB
					dB(A)	
Buses, Trains	1-1.7	79-85	2.25-2.7	90-93	84-86	76-79
Commercial Jet Aircraft - Short Haul	1.1-1.3	82-84	2.7-3.1	89-90	82-84	74-76
Commercial Jet Aircraft - Long Haul	1.2-1.7	79-83	3.0-3.3	88-89	81-89	74-75

[1] For communicating voice (Reference 39).

[2] Typical range of side-by-side seat spacing – 5 inches.

[3] Typical range of front-to-back seat pitch.

[4] Excess loss by barrier or voice directivity.

Daily Community Noise Equivalent Level (CNEL)

Community noise equivalent level, in decibels, represents the average daytime noise level during a 24-hour day, adjusted to an equivalent level to account for the lower tolerance of people to noise during evening and nighttime periods relative to the daytime period. Community noise equivalent level is calculated from the hourly noise levels by the following:

$$\mathrm{CNEL} = 10 \log \frac{1}{24} \left[\sum \mathrm{antilog} \frac{\mathrm{HNLD}}{10} + 3 \sum \mathrm{antilog} \frac{\mathrm{HNLE}}{10} + 10 \sum \mathrm{antilog} \frac{\mathrm{HNLN}}{10} \right]$$

Where

HNLD are the hourly noise levels for the period 0700 - 1900 hours;

HNLE are the hourly noise levels for the period 1900 - 2200 hours;

HNLN are the hourly noise levels for the period 2200 - 0700 hours;

and $\sum$ means summation.

Hourly Noise Level (HNL)

The hourly noise level, in decibels, is the average (on an energy basis) noise level during a particular hour. Hourly noise level is determined by subtracting 35.6 decibels (equal to 10 $\log_{10}$ 3600) from the level of the time-integrated A-weighted squared sound pressure measured during the particular hour.

Residual Noise Level

The temporal pattern of an A-weighted noise level measurement of community noise is generally characterized by two features. The first is the variation in peak levels caused by street traffic, aircraft, and other single event noises. The second feature is that noise level characterized by a fairly steady lower level upon which are superimposed increased levels of the single events. This fairly constant lower level is called residual noise level. The continuous noise one hears in the backyard at night when no single source can be identified and which seems to come from "all around" is an example of residual noise.

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APPENDIX C

NOISE GENERATOR CHARACTERISTICS

This appendix provides a detailed analysis of the characteristics of the principal noise generators in the transportation category. The noise sources to be analyzed are:

- jet engines,
- propellers and rotors,
- internal combustion engines, and
- tires.

C.1 Jet Engine Noise

There are three primary sources of noise on a commercial jet aircraft: engines, boundary layer pressure fluctuations and internal equipment. Engines produce noise at inlets and at the exhaust regions of fan exit ducts and the primary nozzle. Pressure fluctuations in the fuselage boundary layer excite structural components that in turn radiate acoustic energy into the aircraft interior. Equipment such as pumps, blowers and auxiliary power plants installed on an aircraft create noise problems in aircraft interiors. The latter two noise sources are the primary contributors to the noise levels in the passenger cabin during cruise. The major aircraft noise problems, however, are associated with the noise levels imposed upon communities adjacent to large airports. Noise generated by the jet engines constitutes the dominant component in producing this noise impact.

The two principal sources of noise in a jet engine are the jet exhaust and the fan/compressor. As illustrated in Figure C-1, for the case of a low bypass-ratio turbofan engine, jet noise radiates mainly toward the rear of the engine. Fan/compressor noise radiates forward out through the engine inlet and aft through the fan exhaust duct. Figure C-2 shows the effect of engine power setting on the relative contributions from the jet and fan noise sources. On takeoff, the jet noise contributes measurably to the overall noisiness. During landing approaches, however, the fan

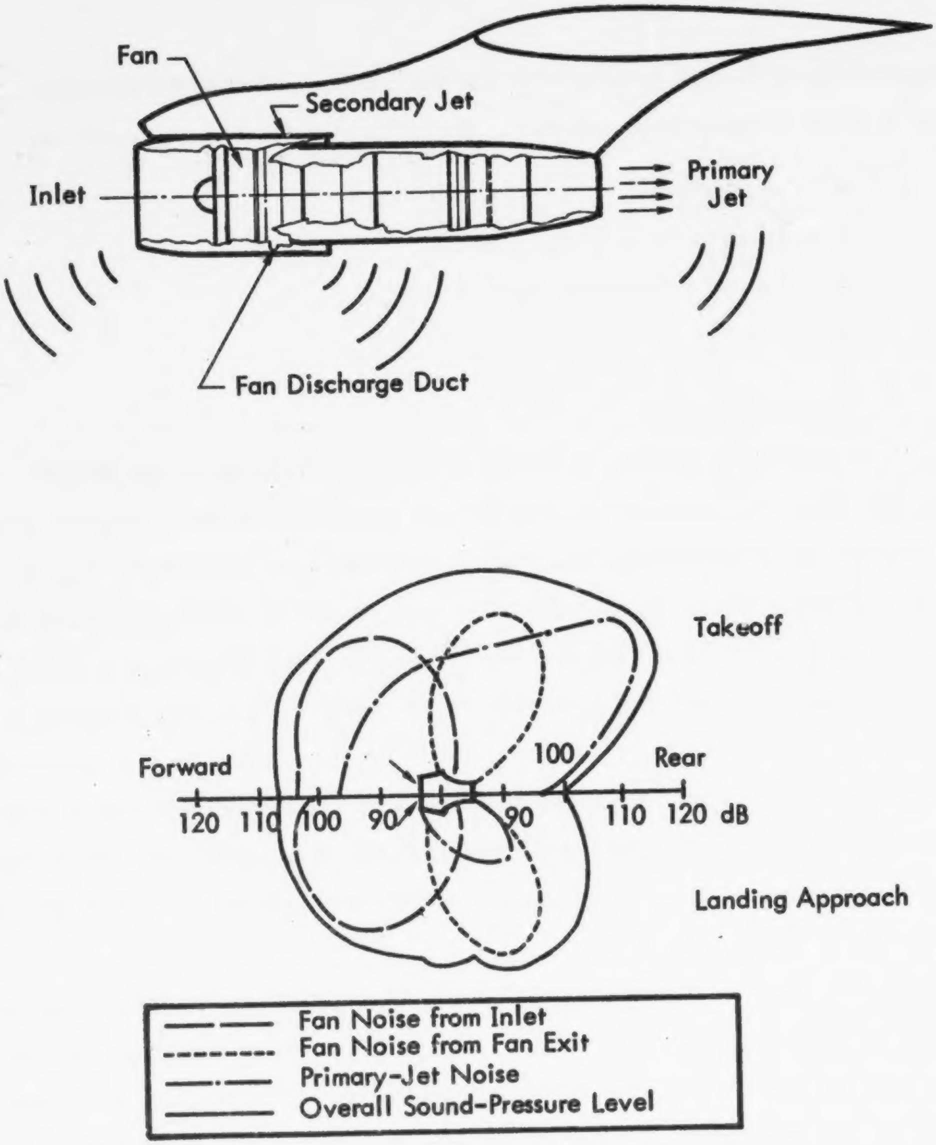

Fan
Secondary Jet
Inlet
Primary Jet
Fan Discharge Duct
Takeoff
Forward
100
Rear
120 110 100 90 90 110 120 dB
Landing Approach
Fan Noise from Inlet
Fan Noise from Fan Exit
Primary-Jet Noise
Overall Sound-Pressure Level

Figure C-1. Turbofan-Engine Noise Sources and Distribution

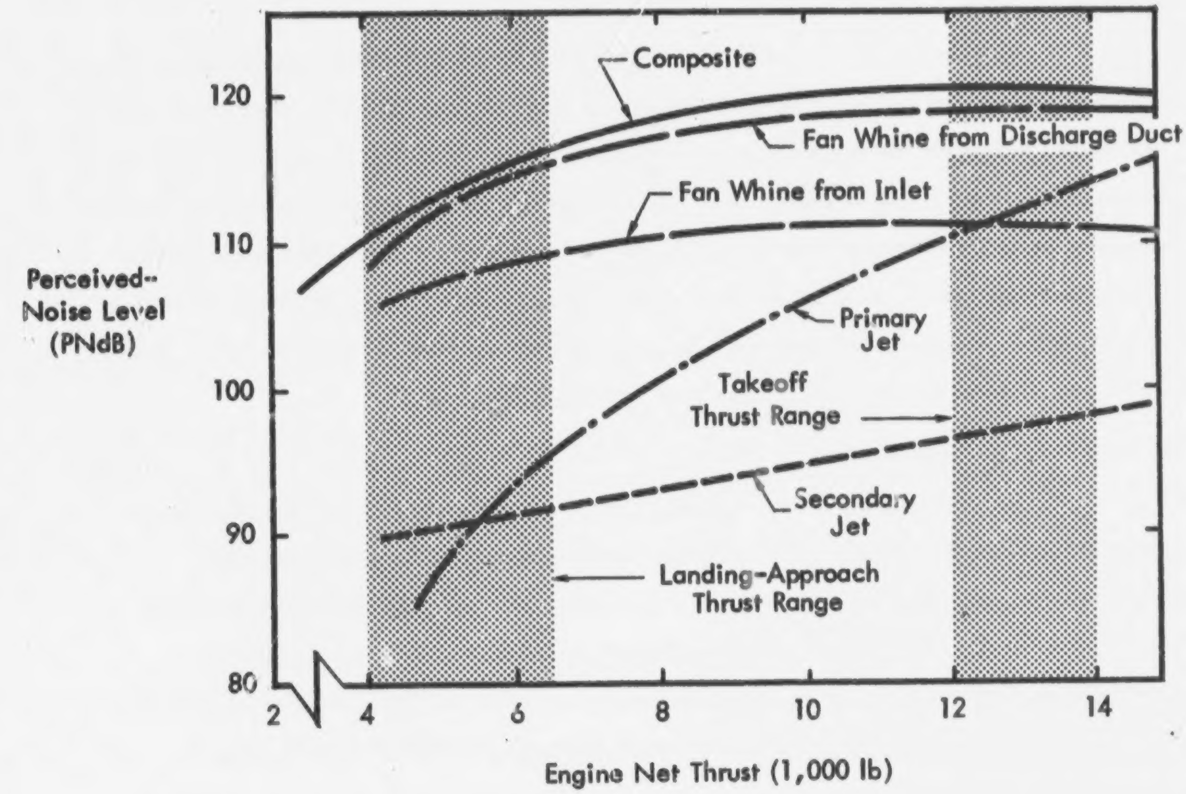


Figure C-2. Turbofan-Engine Noise at 400-Foot Altitude whine from the inlet and discharge ducts is 10 to 20 PNdB higher than the jet exhaust noise.

Engine design is a critical governing factor in determining the balance between jet and fan noise. In the early turbojet engines, the jet noise component was dominant throughout the range of power settings. Subsequent high bypass-ratio turbofan engines generate significantly reduced jet noise levels. However, as the fan noise radiation is reduced through improved fan design technology and fan duct noise attenuation, both sources of noise retain their significance in determining the total jet engine noise levels. The following two sections contain brief accounts of the generation and radiation characteristics of these sources of jet engine noise.

C.1.1 Jet Exhaust Noise

The noise generation processes in the exhaust wakes of current and anticipated future turbofan engines are dominated by quadrupole noise radiation. This mechanism is caused by the turbulent mixing that occurs along the boundary between the high-velocity exhaust jet and the quiescent atmosphere. The mixing process generates a series of flow fluctuations with small turbulent eddies formed close to the nozzle orifice. Increasingly larger eddies are generated within the developing-mixing layer progressively farther downstream, as illustrated in Figure C-3. However, these fluctuations degenerate into smaller scale structures. They also interact with each other and with the mean flow to form both larger and smaller eddies. This interaction results in a distribution of turbulence scales at any location within the mixing layer, with the mean turbulence scale proportional to the local mixing layer width.

The acoustic pressure fluctuations associated with the turbulence fluctuations are distributed in a corresponding manner, with the peak frequencies generated varying continuously from high frequencies in the thin mixing layer close to the nozzle exit to low frequencies in the wide mixing layer far downstream. However, once generated, the acoustic waves interact with other turbulent structures (diffraction) and mean flow gradients (refraction) to emerge from the jet flow with different directional and physical characteristics than originally emitted. These phenomena are qualitatively illustrated in Figure C-3.

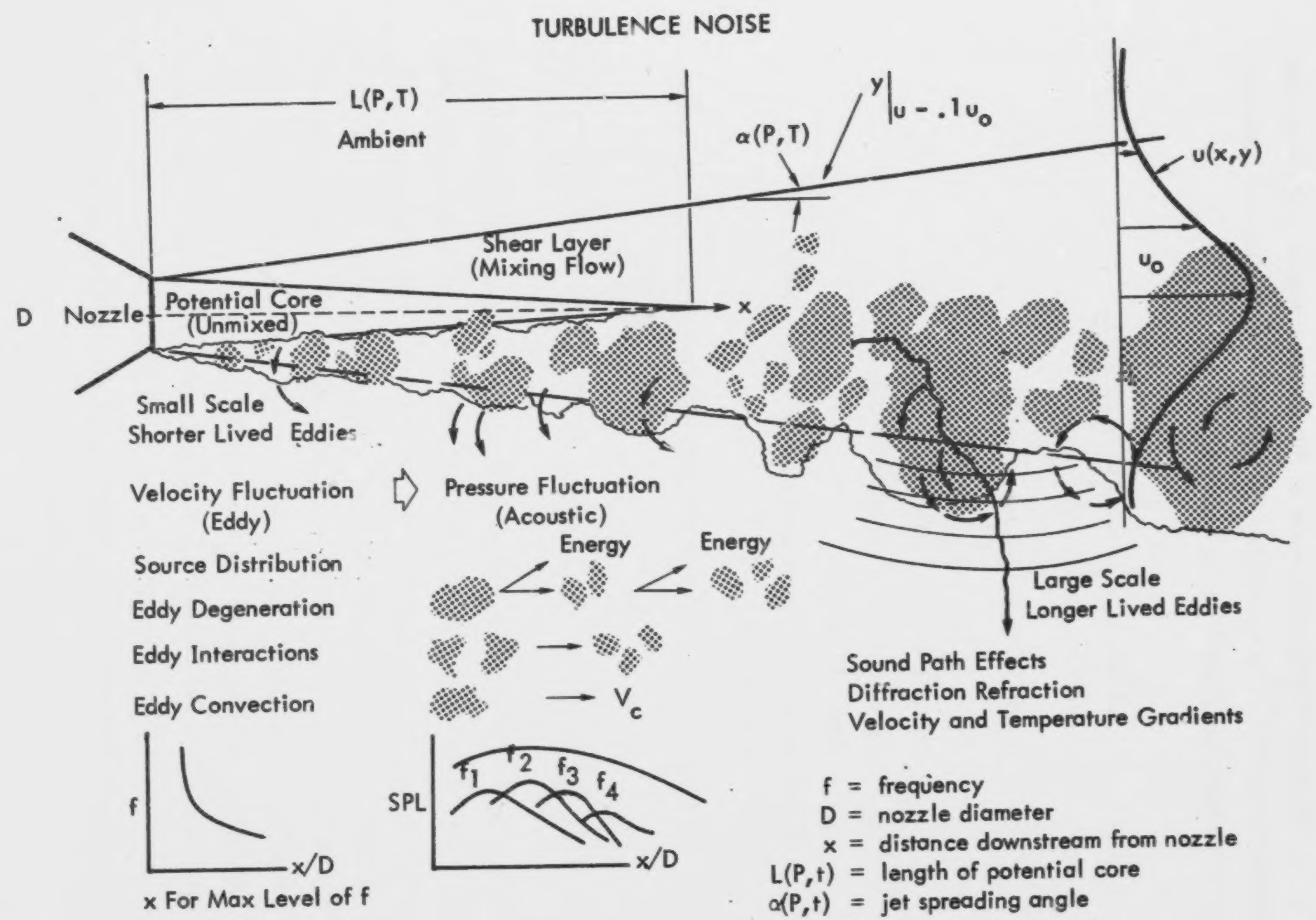

TURBULENCE NOISE
L(P,T)
Ambient
y|u - .1u₀
α(P,T)
u(x,y)
u₀
Shear Layer (Mixing Flow)
D
Nozzle
Potential Core (Unmixed)
x
Small Scale Shorter Lived Eddies
Velocity Fluctuation (Eddy)
Pressure Fluctuation (Acoustic)
Source Distribution
Eddy Degeneration
Eddy Interactions
Eddy Convection
Energy
Energy
V_c
Large Scale Longer Lived Eddies
Sound Path Effects
Diffraction Refraction
Velocity and Temperature Gradients
f
x/D
x For Max Level of f
SPL
f1
f2
f3
f4
x/D
f = frequency
D = nozzle diameter
x = distance downstream from nozzle
L(P,t) = length of potential core
α(P,t) = jet spreading angle

Figure C-3. Jet Noise Generation

The basic mathematical model of this noise generation process was first formulated by Lighthill[1,2] who combined the equation of continuity and momentum into the inhomogeneous Lighthill wave equation:

$$\frac{\partial^2 \rho}{\partial t^2} - a_o^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i \, \partial x_j}$$

where T_{ij} = Lighthill's turbulence stress tensor

$= \rho u_i u_j + P_{ij} - a_o^2 \rho \delta_{ij}$

u_i = velocity in the i direction

a_o = speed of sound in the uniform medium

ρ = density of the flow

P_{ij} = tensor incorporating pressure and viscous terms

δ_{ij} = Kronecker delta

The well-known solution of this differential equation may be written:

$$\rho(\underline{x}, t) = \frac{1}{4\pi a_o^2} \iint \frac{\partial^2 T_{ij}(\underline{y}, \tau)}{\partial y_i \, \partial y_j} \; \frac{\delta\left(t - \tau - \frac{|\underline{x} - \underline{y}|}{a_o}\right)}{|\underline{x} - \underline{y}|} \; d^3\underline{y} \, d\tau$$

Numerous theoretical investigations of jet noise generation have arrived at analytical results by means of careful manipulation of this solution.[3-6] The approach has been developed to a high degree of sophistication and permits qualitative estimates of the noise radiation as a function of the flow velocity and Mach number. However, the Lighthill theory has its basic limitations. It is not well suited to describe flows in which the speed of sound and the mean density vary. Therefore, the effects of temperature and temperature gradients, although implicit in the formal solution, are usually neglected. In addition, the connected path of sound through the mean shear layer is not readily accounted for. These restrictions on the application of the Lighthill theory have resulted in the formulation of new mathematical approaches by various investigators.[7-9]

These will not be discussed here, since they have not brought on improved techniques for the quantitative evaluation of jet noise radiation.

The application of dimensional analysis to Lighthill's solution yields the dimensional law for the intensity of the acoustic radiation from a jet flow to:

$$I \sim \frac{\rho^2 U^8}{\rho_o a_o^5} \left(\frac{D}{r}\right)^2 \frac{1}{(1 - M \cos \theta)^5}$$

where

I = acoustic intensity

U = flow velocity

ρ_o = atmospheric density

D = flow dimension (jet diameter)

M = flow Mach number

r = source-observer distance

θ = angle subtended by source-observer with respect to flow direction

This result has been well substantiated by experiment, although the U^8 law somewhat overestimates the intensity at high jet velocities. Furthermore, the empirical dependence of intensity on the jet density ρ is a function of the jet velocity. Thus, ρ^2 appears to correlate the experimental data at jet velocities greater than 1800 feet/second, whereas at lower speeds, ρ provides the better correlation parameter. With certain similarity assumptions concerning the variation of the peak frequency f, the mean velocity U, and the wake diameter D with distance along the jet axis, the above equation leads to expression for the power spectral density of the sound power emitted by the jet flow. At high frequencies well above the typical frequency $f_o = 0.2\, U_e/D_e$ defining the peak of the power spectrum, the asymptotic expression becomes:

$$\frac{dW}{df} \sim f^{-2}$$

where

W = acoustic power

f = frequency

subscript e = nozzle exit

At the low frequency limit, the corresponding variation is:

$$\frac{dW}{df} \sim f^2$$

Figure C-4 shows a normalized sound power spectrum obtained from measurements on a wide range of jet engines and scale model air jets.[10] The spectrum shows the theoretically predicted trends at the low and high frequency limits.

Figure C-5 presents a generalized correlation of the peak polar sound pressure levels generated by jet engine exhausts and scale model air jets.[11] The correlation on the basis of ρ yields acceptable data scatter, although the increasing spread of the data at the low velocity end is of particular note. The cause of this anomaly is additional noise generated upstream of the nozzle exit and propagating out through the jet wake into the far field. This noise is generally dipole (U^6) in character, hence its dominance at low velocities. Referring to Figure C-5, line B-B shows the peak polar sound pressure levels measured with a noise-generating obstruction installed in the upstream pipe; line C-C shows the same measurements with the obstruction removed. Line D-C is obtained if the upstream pipe is carefully treated to eliminate all possible upstream sources of noise. The immediate conclusion from this is that the line A-B, which represents data from a wide range of jet engines and model rigs, is influenced by sources other than the jet mixing noise. In the case of scale model air jets, these sources may be simple upstream obstructions. For the full-scale jet engines, however, there are numerous additional and as yet incompletely defined sources. These additional sources are often termed engine core noise and are of significance for new technology engines which have subsonic primary exhaust velocities.

Current and advanced technology turbofan engines are characterized by having a lower velocity fan exhaust stream surrounding the primary jet exhaust. The generation of the noise field by these multiflow jets is even more complicated than for a

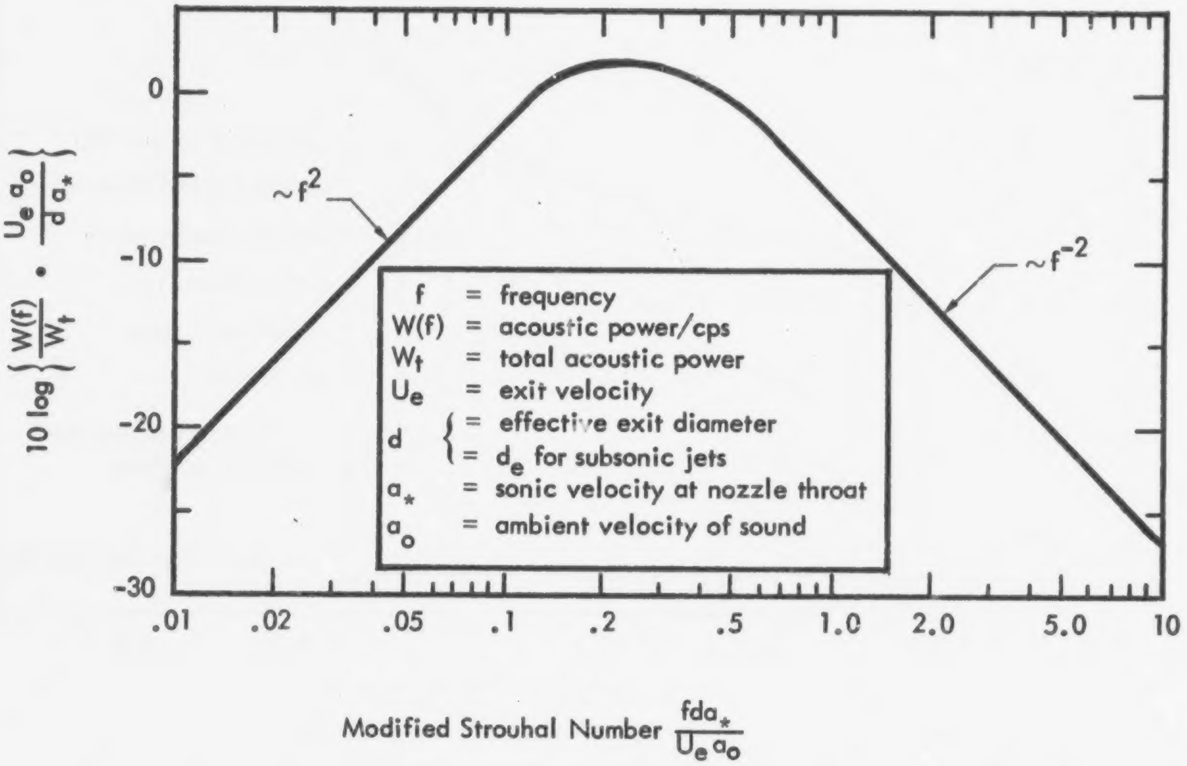


Figure C-4. Normalized Power Spectrum for Axisymmetric Jets Issuing from Convergent Nozzles (Data from Eldred, Reference 10)

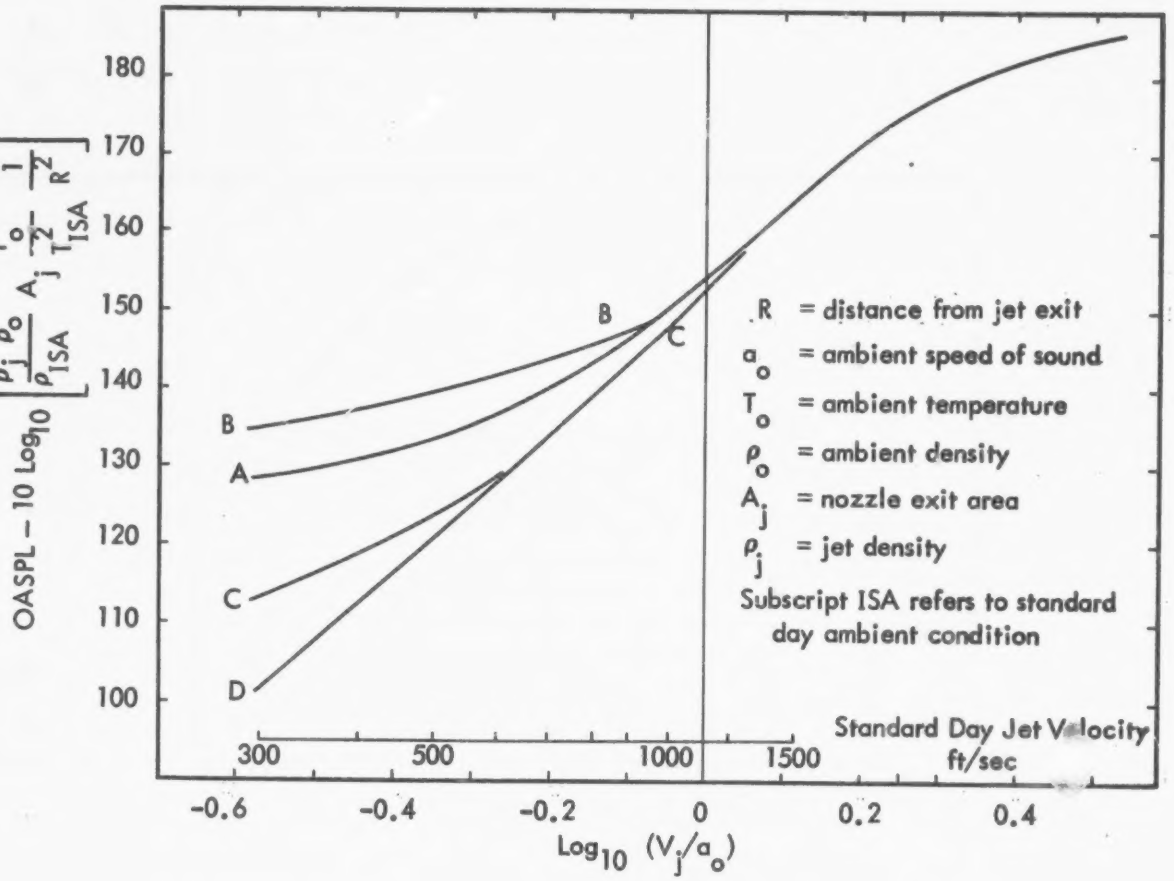


Figure C-5. Jet Noise Correlation Peak Polar OASPL
(Data from Bushell, Reference 11)

single jet. One significant aspect of jet noise generation is that the sound results from an extended source volume over the length of the mixing flow. Variations to this mixing flow caused by the interaction of the two jets will result in different noise characteristics. A recent experimental study[12] included a detailed examination of the effects of the bypass flow on the total noise radiation, resulting in the following conclusions:

- The reduction in jet noise due to shrouding of primary flow by secondary flow is maximum for a secondary to primary velocity ratio near 0.5, on a constant thrust basis.
- The reduction in jet noise increases with increasing area ratio.
- The noise reduction is independent of the pressure ratio of the primary nozzle and the total temperature of the primary flow.

These concepts are illustrated in Figure C-6. A noise reduction of 10 PNdB at a 1500-foot sideline is achieved at an area ratio of 10 as compared with a single nozzle jet (area ratio zero) having the same thrust.

C.1.2 Fan/Compressor Noise

Compressors generate two distinct types of sound, broadband and harmonic. The random broadband sound extends over a very wide range of frequencies. The harmonic sound has one or more fundamentals corresponding to the blade passage frequencies of the compressor stages, together with associated harmonics. A third type of compressor noise, combination tones, is important in high bypass ratio turbofan engines operating at takeoff power. A typical compressor noise spectrum is shown in Figure C-7.

Broadband Noise

Broadband noise is attributable to the action of turbulence and other irregular flow disturbances upon the compressor blades. Sharland[13] studied compressor broadband noise radiation both theoretically and experimentally, and his work forms much of the basis for present knowledge. Basically, there are two primary mechanisms for broadband noise generation. The first is associated with the passage of a blade into

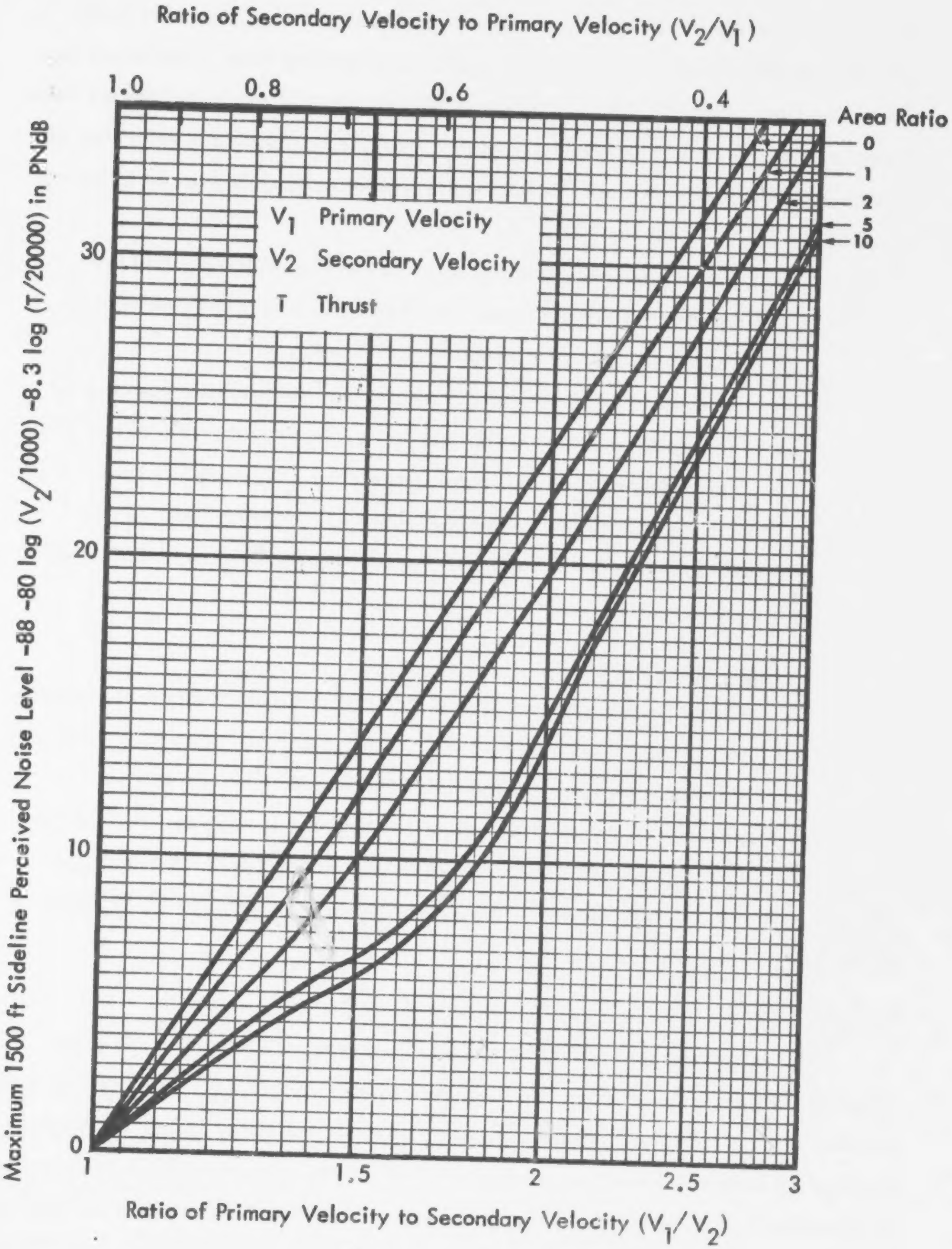


Figure C-6. Effect of Velocity Ratio on Maximum Perceived Noise Level on a 1500 ft Sideline Using Secondary Velocity as Reference at Constant Thrust (Data from Eldred, Reference 12)

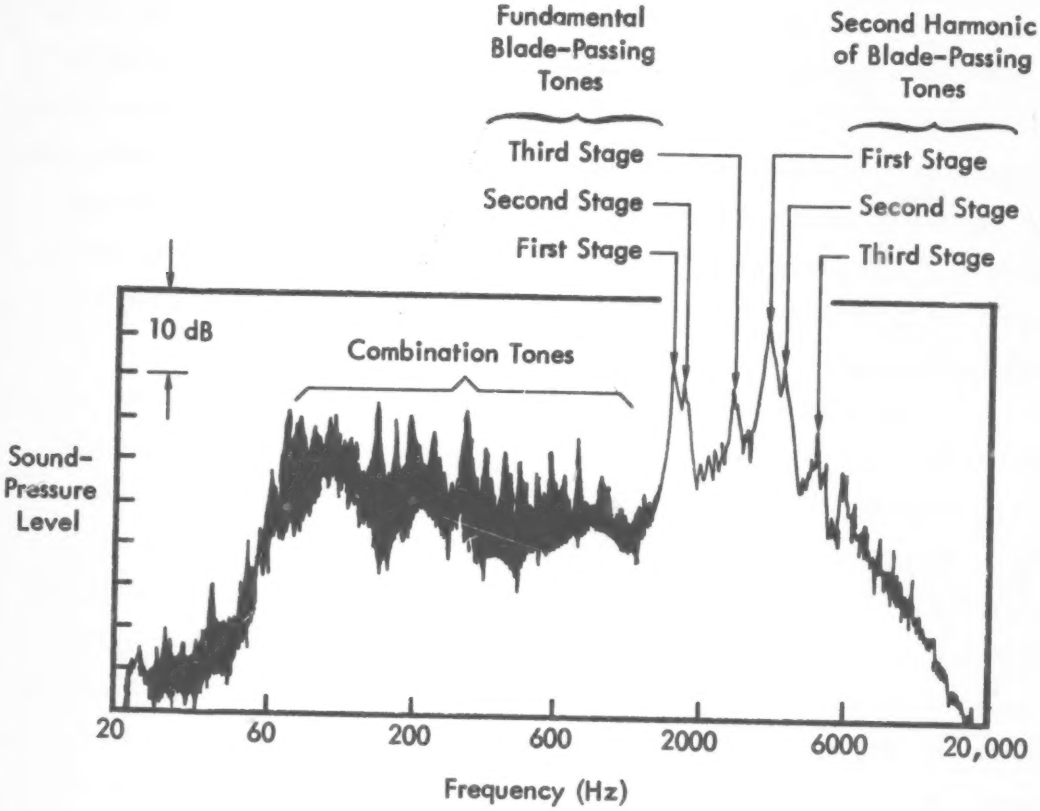


Figure C-7. Typical Compressor-Noise Spectrum an existing region of turbulent flow caused by upstream disturbances, which in practice may be various compressor stages of rotor, stators, inlet guide vanes, struts, et cetera. The velocity fluctuations in the oncoming flow generate lift fluctuations at the blade surface, which in turn radiate noise. The second mechanism is essentially self-generated and arises even for a blade operating in undisturbed air. At sufficiently high Reynolds numbers, typical of compressor blading, the boundary layer becomes unstable. In addition to generating direct pressure fluctuations on the blade surface, it gives rise to an unsteady wake which in turn induces pressure fluctuations at the blade trailing edge.

For an infinite rigid surface, the monopole and dipole terms in the equation for sound radiation by turbulence[14] disappear, while the quadrupole term must be integrated over all space including an image turbulence behind the surface. That is, the quadrupole radiation, which is doubled due to reflection, is the only source of noise in this case. However, for a finite surface (e.g. a compressor blade), the reflection is not complete and a magnification of the quadrupole field results. In this case, it is convenient for analysis purposes to regard the surface pressure fluctuations as the source of noise, which is therefore of a dipole nature. These observations suggest that large surfaces will radiate as U^8 while small ones will radiate as U^6. Whether the surface is "large" or "small" depends upon its size relative to both acoustic (λ) and turbulence (ℓ) wavelengths.

Since the latter quantities are related by the flow Mach number $N = \ell/\lambda$, one can state that for a surface of dimension d, the radiation is quadrupole if $M >> \ell/d$, and dipole if $M << \ell/d$. Since ℓ is also proportional to frequency, higher frequencies are more likely to radiate as quadrupoles.

The two sources of random sound discussed above can be related to two basic situations. The first is the production of noise on a blade due to the boundary layer actually set up on that blade. This is termed "self-generated" noise: it is small-scale (i.e., high frequency), and it quadrupole in nature. The second is the noise produced by passage of the blade through turbulence generated upstream of the blade.

This is "externally generated," has a much larger scale (lower frequency), and is dipole in character.

A dimensional analysis of the various sources yielded the following relationships for the total power (W) radiated from an area (S):

External Turbulence

$$W = \frac{1}{6} \rho_o \frac{U^4 M^2 S}{a_o} \qquad \text{(dipole)}$$

Self-Induced Boundary Layer Pressure Fluctuations

$$W = 10^{-7} \frac{\rho_o U^6 S}{a_o} \qquad \text{(dipole)} \qquad a_o^3$$

Reflection of Boundary Layer "Self-Noise"

$$W = 6 \times 10^{-8} \frac{\rho_o U^8 S}{a_o} \qquad \text{(quadrupole)} \qquad a_o^5$$

It turns out that for turbulence levels in excess of 0.001, the first equation dominates and suggests that "external turbulence" is a very significant noise source.

The prediction of broadband noise radiation, although analytically straightforward, is critically dependent upon the nature of the spatial correlation of the surface pressure fluctuations. The problem reduces to that of estimating the variation of spanwise and chordwise correlation lengths with the compressor operating configuration.

Harmonic Tones

The main difference between harmonic and broadband noise generation is that the former is associated with periodic rather than random flow disturbances in the compressor duct. Otherwise, the mechanisms are very similar. The word "periodic" here essentially includes the fundamental or steady velocity terms which are associated with the steady thrust and torque forces acting upon the blades. Since this is the basic mechanism of propeller noise radiation, this source of compressor sound is sometimes referred to as the propeller mode. Its origin was first analyzed by Gutin,[15] whose theory is still widely used for propeller noise prediction.

Of much more importance is the noise radiated by the action of fluctuating forces upon the blades due to the presence of "higher harmonic" flow fluctuations. These flow fluctuations are due to the presence of obstructions such as struts, guide vanes, or stators, which produce velocity defects and potential flow interactions. Figure C-8 shows the basic geometry for stator-rotor interaction. Several alternative theories are available for the prediction of harmonic noise generation. Lowson's theory[16] will be used to describe the problem.

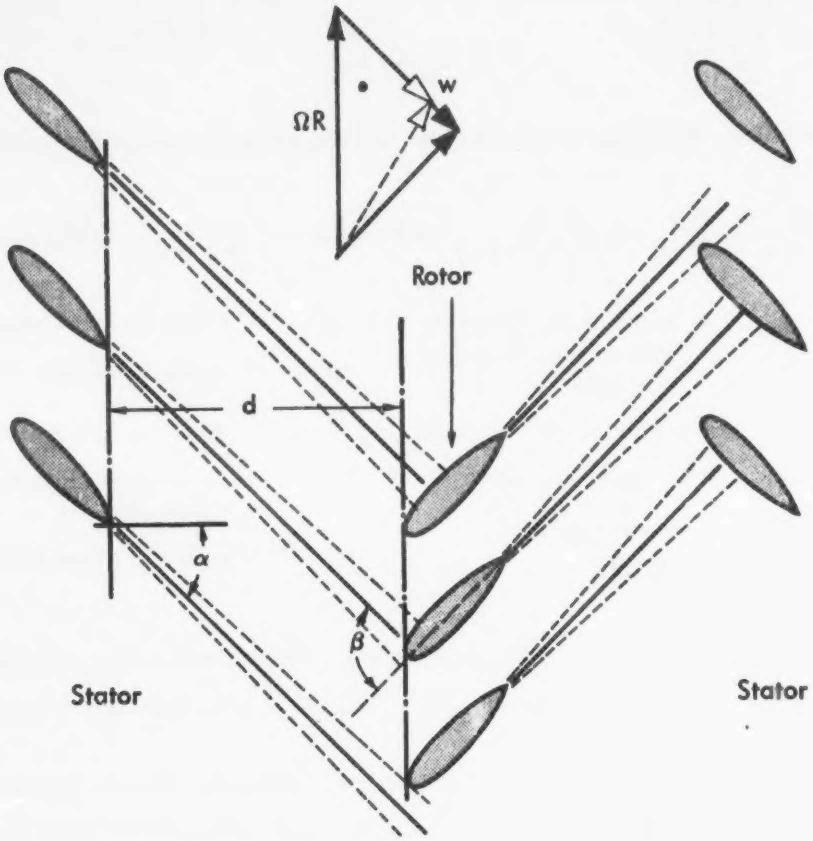
Like Curle's theory[14] of sound radiation by surfaces, Lowson's analysis starts with Lighthill's basic equation for aerodynamic sound generation:

$$\frac{\partial^2 \rho}{\partial t^2} - a_o^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial Q}{\partial t} - \frac{\partial F_i}{\partial x_i} + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

The left-hand side is the acoustic-wave equation, and on the right-hand side are the three source terms corresponding to monopole, dipole and quadrupole radiation, respectively. The only term of significance for most applications is the second, which corresponds to noise radiation by surface forces. Retaining only this term, the solution may be written:

$$\rho\left(\underline{x}, t\right) = -\frac{1}{4\pi a_o^2} \int\int \frac{\partial F_i\left(\underline{y}, \tau\right)}{\partial x_i} \; \frac{\delta\left(t - \tau - \frac{|\underline{x} - \underline{y}|}{a_o}\right)}{|\underline{x} - \underline{y}|} d^2 \underline{y} \, d\tau$$

where the integration must be performed over the entire source region.



ΩR
w
Rotor
d
α
β
Stator
Stator

R = rotor radius
Ω = rotational frequency in radians/sec
d = stator-rotor spacing
α = stator exit swirl angle
β = rotor turning angle
w = flow velocity

Figure C-8. Basic Wake Geometry
(Data from Lowson, Reference 16)

If one of the aerodynamic force components acting on the blade, namely the thrust, is written in its Fourier form, the nth harmonic can be written:

$$T = T_n \cos n\phi$$

Upon substitution, the integral solution can be integrated for one revolution to yield:

$$c_m = \frac{mB^2 \Omega}{4\pi a_o r} \left\{ T_n \cos \theta \right\} \left\{ J_{mB-\lambda} (mBM \sin \theta) + (-1)^{\lambda} J_{mB+\lambda} (mBM \sin \theta) \right\}$$

where c_m = sound pressure amplitude of the nth sound harmonic

m = order of the harmonic

B = number of blades

Ω = rotational speed

J_{mB} = Bessel function of order mB

M = blade Mach number

a_o = speed of sound

r = distance from blade

θ = angle from fan axis to field point

λ = multiple of load harmonic

When $n = 0$, this reduces to the Gutin equation. The important thing to note about this equation for any value of m is that any thrust harmonic can generate any sound harmonic.

Outside a certain range of frequencies, however, the acoustic efficiencies of these harmonics are low; for practical purposes, only values of the load harmonic number (k) need be considered lie in the range:

$$\frac{mB}{V} (1 - M \sin \theta) \leq k \leq \frac{mB}{V} (1 + M \sin \theta)$$

To utilize the result, it is necessary to understand that the velocity and hence force fluctuations occur each time a blade passes through a disturbance associated with upstream obstacles. For example, if a rotor is located downstream from a stator with V vanes, then the fluctuations experienced by each blade have a fundamental radian frequency of $V\Omega$, where Ω is the rotational speed. Similar arguments can be applied to the stator.

Such equations, although based upon a number of simplifying assumptions, give convenient solutions for the sound radiated by rotors and stators, which have been demonstrated by Ollerhead and Munch[17] to be remarkably accurate for the first harmonic radiation by typical fan configurations. However, these computations, like all solutions to compressor noise generation, are only as accurate as the force-input terms. These correlations were obtained with use of airfoil-wake data to estimate the harmonic content of velocity profiles behind compressor stages. The scatter in the data shown in Figure C-9 reflects this uncertainty in the force-input terms. Typical velocity profiles were assumed for the theoretically determined line in the figure. Improved knowledge of these profiles should close the discrepancy between the theoretical and experimentai noise levels.

Combination Tones

Combination tone noise is radiated from the inlet of turbofan engines having fan blades rotating with supersonic tip speeds; hence, it is a prominent type of noise from the current high bypass ratio turbofan engines at takeoff power. This effect is illustrated in Figure C-10.[18] Unlike the sound field produced by fans at subsonic operation, where discrete tones are produced at harmonics of blade passage frequency, fans at supersonic tip speeds generate a multiplicity of tones at essentially all integral multiples of engine rotation frequency.

The essential features of combination tone generation are well established.[18,19] Shock waves are produced at the leading edge of each blade and spiral forward of the fan, conveying sound energy out of the inlet to the far field. The waveforms are fairly uniform close to the fan, both in shock amplitude and in spacing between shocks. Farther forward of the fan, however, much of the blade-to-blade periodicity is lost and variations in shock amplitude and spacing become prominent. Since the shocks form a fairly steady but irregular pattern rotating with the fan, the corresponding noise spectrum is composed of a series of tones at harmonics of the shaft rotation frequency.

This loss of blade-to-blade periodicity can be explained on the basis of finite amplitude wave theory. Close to the fan, the intervals between shocks are quite

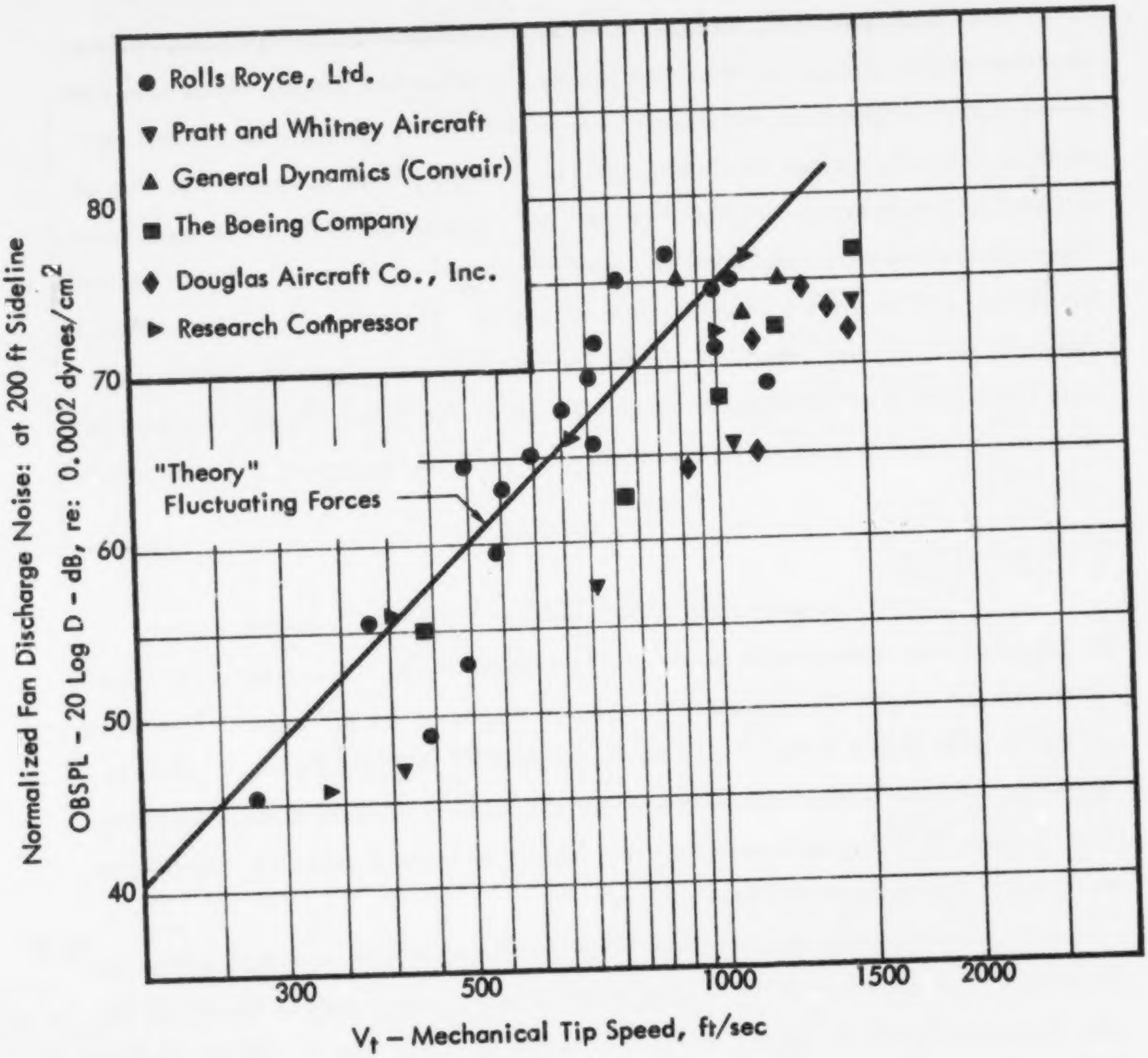


Figure C-9. Comparison of "Theory" and Experiment. Maximum Fan Discharge Noise in Octave Band Containing Fundamental Blade Passage Frequency (Data from Lowson, Reference 16)

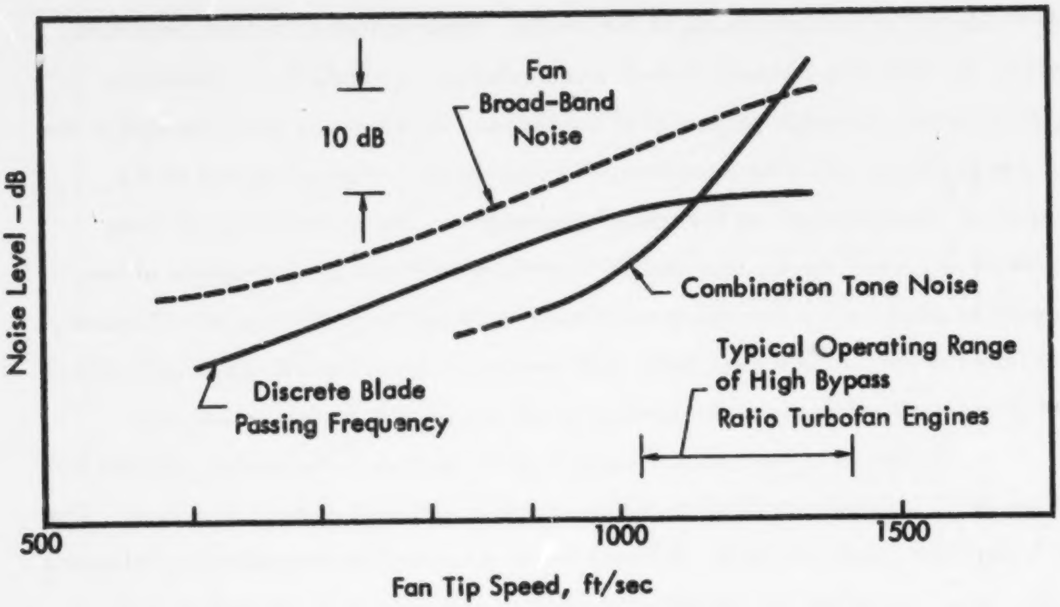


Figure C-10. Variation of Fan Noise Components with Fan Tip Speed
(Data from Kester, Reference 18)

uniform due to the regular spacing of the blades. Some variation in shock amplitude, however, is inevitable because of small manufacturing variations in the incidence angles and other geometric properties of the blades. As the waves spiral forward of the fan, this amplitude variation creates significant interval variation because of the influence of shock strength on the rate of propagation. Strong shocks travel faster than relatively weak shocks; thus an initial small variation in shock strengths of two consecutive shocks will cause the spacing between these shocks to vary with distance away from the fan. At the same time, both shocks are decaying and they eventually reach a stable situation where the spacing is unchanged with further propagation.

A feature of the combination tone noise spectra in the engine far field is that two fans, although identical in design, produce different spectral signatures. The fact is that each blade is slightly different within well defined manufacturing tolerance bands. When the blades are assembled to produce fans, the small deviations of each fan from design will be different from fan-to-fan. A deterministic prediction procedure for a given design would thus require knowledge of the variation in manufacture of all blades on each fan. Since this is impractical both in advance of and during production, an estimate of the average spectrum for a given fan design represents the practical limits in combination tone prediction. This average will not only depend on relevant geometric blade parameters, but also on their standard deviations from design.

C.2 Propeller and Rotor Noise

The mechanisms by which rotors, propellers and fans produce intense sound pressures have been the subject of much work, especially in recent years. Traditionally, noise generated by propellers has been separated into two parts called the rotational and vortex components. Rotational or periodic noise here describes all sound which is identified with discrete frequencies occurring at harmonics of the blade passage frequency.

Vortex or broadband noise describes the modulated sound produced by the unsteady pressure field associated with vortices shed from the trailing edge and tips of the blades, as well as some of the noise sources associated with turbulence effects in the air stream. The helicopter rotor deserves separate consideration. Although much of its noise can be explained in terms of propeller noise sources, there are a number of other sources exclusive to that device which make significant contributions to the overall levels.

Rotational Noise

All real rotating airfoils, i.e., those having thickness, have a pressure distribution when moving relative to the surrounding medium. This pressure distribution can be resolved into a thrust component normal to the plane of rotation and a torque component in the plane of rotation. This pressure field on the air is steady relative to the blade and rotates with it if operating under conditions of uniform inflow. For non-uniform inflow, such as a helicopter rotor in steady forward flight, the difference in relative blade speed during forward and backward motion of the blade relative to the flight path requires a cyclic incidence variation to provide a reasonably uniform lift over the disc. To a first approximation, the forces on the air next to the disc would be constant under these conditions; the effects of incidence changes would appear only as variation of chordwise loading over the blade. From a fixed point on the disc, the rotating field appears as an oscillating pressure. The frequency of the oscillation is the frequency with which a blade passes that point (blade passage frequency) and the waveform of the oscillating pressure is determined by the chordwise distribution of pressure on the blades.

In addition to experiencing a fluctuating force, an element of air in the disc will be physically moved aside by the finite thickness of the blade. In a fixed frame of reference, this displacement is equivalent to a periodic introduction and removal of mass at each element of air near the disc. The rate of mass introduction at a point, which is determined by the blade profile, incidence and speed, can then be expressed as the strength of a simple source. Up to values of resultant tip speed approaching sonic, thickness noise is generally found to be small compared with the noise arising from torque and thrust. At higher tip speeds, however, it may assume equal importance.

Interaction and Distortion Effects

Certain periodic effects are usually identified with helicopter rotors, but may occur to a lesser degree in propellers. Impulsive noise, blade bang or blade slap may consist of high-amplitude periodic noise plus highly modulated vortex noise caused by impulsive fluctuating forces on the blades. The mechanisms by which these forces may arise are: (1) blade-vortex interaction, (2) periodic stalling and unstalling of a blade, and (3) shockwave formation and collapse due to unsteady periods of local supersonic flow. The first and second conditions (and possibly the third) may occur (1) when a blade passes through or near a tip vortex, or (2) when an unsteady wake is generated by a preceding blade. Operation in this unsteady flow condition leads to strong fluctuating forces. Here, aeroelastic properties may become significant parameters. The third mechanism may also result directly from operation of a blade at high tip speed (such as an advancing helicopter blade during high speed flight). When high tip speed occurs, blade slap is by far the dominant source of aerodynamic noise.

Vortex Noise

The dominant source of broadband noise is called vortex noise, which has been defined as that sound which is generated by the formation and shedding of vortices in the flow past a blade. For an infinite circular cylinder, normal to the flow and in the range of Reynolds numbers from 10^2 to 10^5, it is well known that the vortices are shed in an orderly vortex street which is a function of cylinder diameter and flow velocity. The process in the case of a rotating airfoil is similar and since there is a different velocity associated with each chordwise station along the span, a broadband of shedding frequencies results. This produces a dipole form of acoustic radiation in which the strength of the source is proportional to the sixth power of the section velocity. Hence the frequencies associated with the area near the tip tend to be of greatest amplitude. Also, since a blade develops lift (thrust), tip and spanwise vorticity of strength proportional to the thrust gradients are generated and shed. Their dipole acoustic radiation combines with that from the trailing edge vortices to make up the so-called vortex noise.

C.2.1 Propeller Noise

As discussed above, the noise produced by an operating propeller has been an object of scientific interest for many years. All of the early work in the aeronautical noise field, both analytical and experimental, was concerned with the propeller noise problem or with allied configurations such as Yudin's work with rotating rods.[20]

Although closely related to the noise produced by rotors and fans, the problem of propeller noise is simpler in some respects because of the configuration and operating conditions of the propeller. The small number of blades in a normal propeller, together with the flow velocity through the propeller disc, minimizes the interference effects due to operation in the wake of preceding blades. The structure and location of the propeller is such that noise due to blade flutter and asymmetrical induced flow are not normally encountered. At moderate tip speeds, i.e., slightly below the onset of compressibility effects, both vortex noise and rotational noise due to thickness are lower than the rotational noise due to thrust and torque. Consequently, most of the noise work on propellers, of both a theoretical and experimental nature, has concentrated on the effects of thrust and torque. In studies dealing with the reduction of overall propeller noise, however, vortex noise has been shown to be an important contributor and in the case of high-speed flight, the level of thickness noise may exceed that of thrust and torque noise.

Rotational Noise

The theoretical work of Gutin[15] provides the equation for the sound pressure of the mth harmonic tone:

$$P_m = \frac{169.3\ mBRM_t}{SA}\left[\frac{0.76\ P_h}{M_t^2} - T\cos\theta\right] J_{mB}(x)$$

where

P = rms sound pressure level (SPL) in dynes/cm^2

m = order of the harmonic

S = distance from propelier hub to observer, ft

R = propeller radius, ft

A = propeller disc area, ft^2

P_h = absorbed power, horsepower

T = thrust, lbs

B = number of blades

M_t = tip Mach number

J_{mB} = Bessel function of order mB

x = argument of Bessel function $0.8\ M_t mB \sin\theta$

θ = angle from forward propeller axis to observer

The expression gives reasonable agreement with experimental results for the first few harmonics of conventional propellers operating at moderate tip speeds and forward velocities. In these circumstances, summation of the square root of the sum of the squares of the solutions to the above expression for $m = 1, 2, 3, 4$ will yield an adequate approximation of the overall sound pressure of the thrust and torque components. Under such conditions, it is a suitable estimate of the total noise as well.

As tip Mach number is reduced to the range between 0.5 and 0.3, experimental results begin to diverge from the predicted values in the direction of higher levels. In this region, vortex noise, which originates in the variable forces acting on the medium during flow past the blade, makes itself known.

Vortex Noise

An equation developed by Hubbard,[21] which was based on Yudin's original work, additional work by Stowell and Deming,[22] and others, is frequently used to calculate vortex noise in terms of SPL:

$$SPL = 10 \log \frac{kA_b (V_{0.7})^6}{10^{16}} \quad \text{(dB at 300 ft)}$$

where

k = constant of proportionality

A_b = propeller blade area, ft^2
$V_{0.7}$ = velocity at 0.7 radius

The expression indicates that vortex noise is a strong function of blade velocity; doubling the blade velocity increases the SPL by 18 dB. The effect of doubling blade area is less severe; the SPL is increased by 3 dB. This suggests that the way to reduce vortex noise is to minimize the tip velocity and to make up the required thrust by increasing blade area as far as possible within the constraints of efficiency and structure. It should be remembered, however, that the vortex noise of propellers does not become significant until the blade velocity is already below normal operational values.

C.2.2 Rotor Noise

Rotational Noise

The study of rotor noise has had the advantage of drawing on the knowledge gained from earlier interest in the propeller. It was found, however, that although propeller noise theory was fairly accurate in describing the sound level of the first harmonic of rotors, it was grossly in error for the higher harmonics. This is not altogether surprising when one considers the relative complexities of the two systems. The propeller that Gutin described was a rigid device rotating in steady, uniform flow. The modern rotor is quite a different system. The main feature of the rotor aerodynamics is the lack of symmetry. In transitional and forward flight, the rotor disc encounters highly nonuniform inflow, and the mechanism by which forward thrust is obtained gives rise to cyclic pitch and fluctuating airloads. Under these operating conditions, velocity fluctuations are induced which give rise to a multitude of blade-loading harmonics. The calculation or experimental determination of these higher harmonic blade loads is extremely complex and has met with only limited success. Many authors[23-25] are of the opinion that all the significant higher harmonic sound effects (except possibly at transonic or supersonic speeds) can be attributed to these unsteady higher harmonic loadings and, further, that any sound harmonic receives contributions from all loading harmonics.

Lowson and Ollerhead[23] have undertaken to avoid the problem of theoretically determining the blade-loading harmonics by deriving empirical harmonic decay laws. A study of the available full-scale blade-loading data revealed that the amplitude of the airload harmonics decayed approximately as some inverse power of harmonic number, at least in the range which covered the first 10 harmonics. For steady flight out of ground effect, the optimum value for the exponent was found to be -2.0, so that the amplitude of the mth loading harmonic was proportional to $m^{-2.0}$. This law was then extrapolated indefinitely to higher frequencies in order to provide some estimate of the higher harmonic airload levels. However, before this could be used as a basis for noise calculation, account had to be taken for phase variations around the rotor azimuth and along the rotor span. It was assumed that the phases could be randomized. In the case of the spanwise loading variations, this was accomplished by the introduction of a "correlation length" concept such as commonly used in turbulence theory. By assuming that the correlation length was inversely proportional to frequency, this resulted in an approximate net effect of adding a further -0.5 to the exponent of the loading power law. Also, an effective rotational Mach number concept is introduced which enables the effects of forward speed to be calculated directly from results for the hover case.

Using these approximations, the rotational noise spectrum for the Bell UH-1 helicopter was calculated for comparison with available measurements. The comparison is shown in Figure C-11. Because of uncertainties regarding the overall levels, they were normalized on the basis of power in the third and higher harmonics. Although for this reason, nothing can be said about overall levels, the agreement, insofar as spectral shape is concerned, is good up to the thirtieth harmonic.

Broadband (Vortex) Noise

The fundamental generation mechanism of broadband and, more particularly, vortex noise from rotors is not yet fully understood. In Yudin's early work with rotating rods, vortex noise was considered to be a viscous wake-excited phenomenon and indeed it must be in that case. However, in the case of a lifting airfoil such as a rotor, the

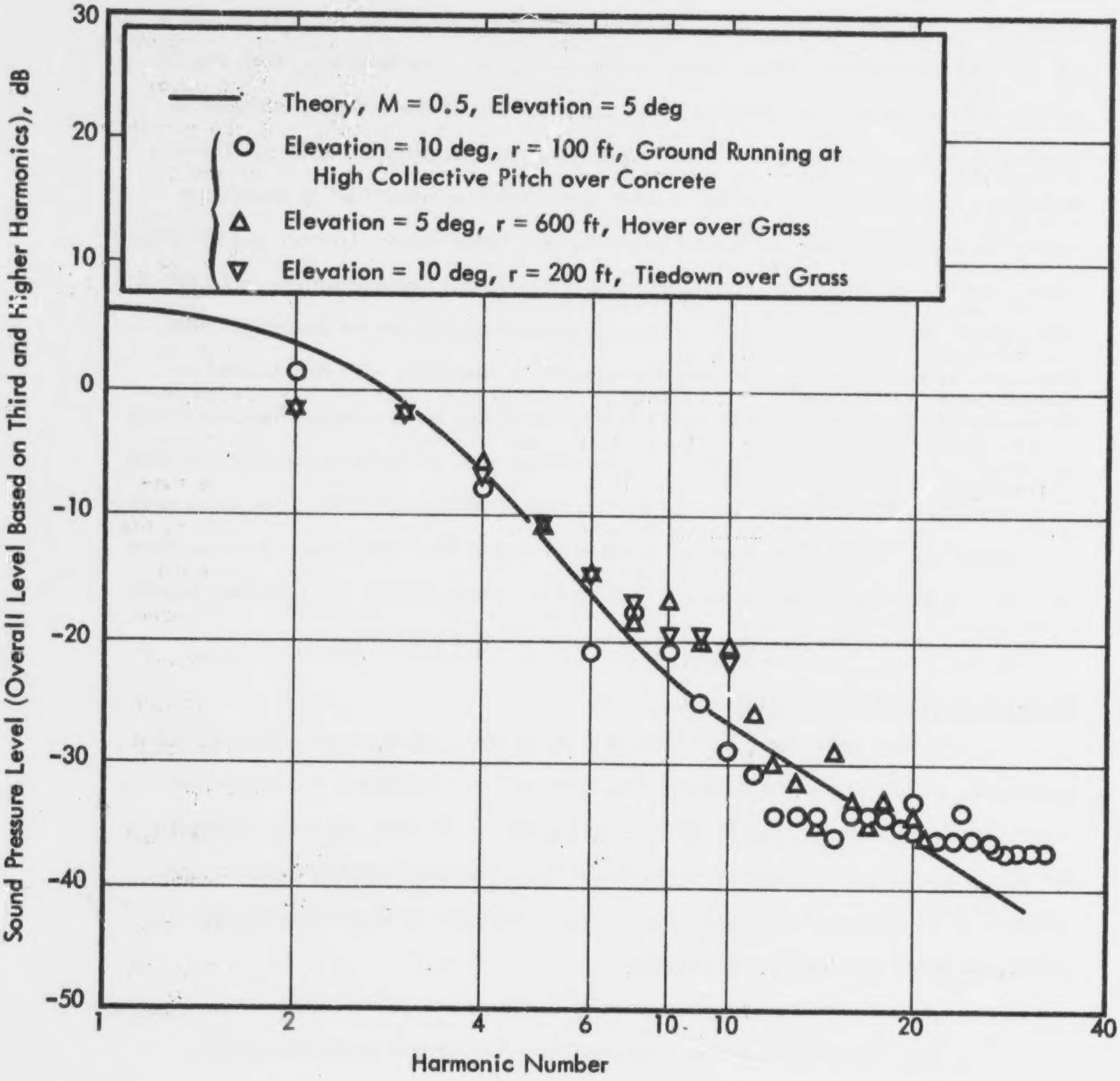


Figure C-11. Noise Spectrum; Comparison of Theory and Experiment For a Two-Blade Rotor (UH-1A and UH-1B) (Data from Lowson/Ollerhead, Reference 23) experimental evidence could support equally well the contention that it is caused by a random movement of the lifting vortex in the tip region. Quite likely, both the tip vortex and the vortex sheet shed from the upper surface of the airfoil contribute in varying degrees, depending on the configuration and operating conditions. There is evidence, however, that a portion of what was originally identified as broadband vortex noise may, in fact, be higher harmonic rotational noise. Lowson and Ollerhead report that the rotational noise of rotors may dominate the noise spectrum up to 400 Hz and higher. At any rate, broadband noise is generated and can be dominant under some rotor operations, e.g., at very low rotational velocities with two-bladed or three-bladed rotors, where even higher harmonics of the blade passage frequency may be inaudible. Hubbard and Regier[26] extended the work of Yudin and postulated that for propellers with airfoil sections, as for rotating circular rods, the vortex noise energy was proportional to the first power of blade area and to the sixth power of the section velocity. Experimental measurements, where they are available and reliable, should be used to evaluate the constant for a particular set of conditions.

Modulation (Blade Slap) Noise

Rotors suffer more from distortion noise than any other aerodynamic noise generator. Blade slap is the colloquialism that has been applied to the sharp cracking sound associated with helicopter rotor noise sources. To date, the only attempt at a quantitative study of the problem seems to be the papers published by Leverton and Taylor.[27,28] In the latest, Leverton lists the three main mechanisms generally postulated for blade slap in the literature:

- Fluctuating forces caused by blade-vortex interaction.
- Fluctuating forces resulting from stalling and unstalling of the blade.
- Shock wave formation due to local supersonic flow; it is suggested that this is either (a) a direct result of operating a blade at a high tip speed, or (b) caused by a blade-vortex interaction.

At the present time, detailed information on these mechanisms is still limited; therefore, it is almost impossible to state which is the most likely mechanism. However, a blade intersecting the tip vortex shed by a preceding blade could itself cause the other two mechanisms to occur. Leverton assumes that blade slap is the direct result of the fluctuating lift caused by the interaction of a blade and a vortex filament. This can be either an actual intersection when a blade cuts a vortex filament or the effect of a blade passing very close to a vortex filament.

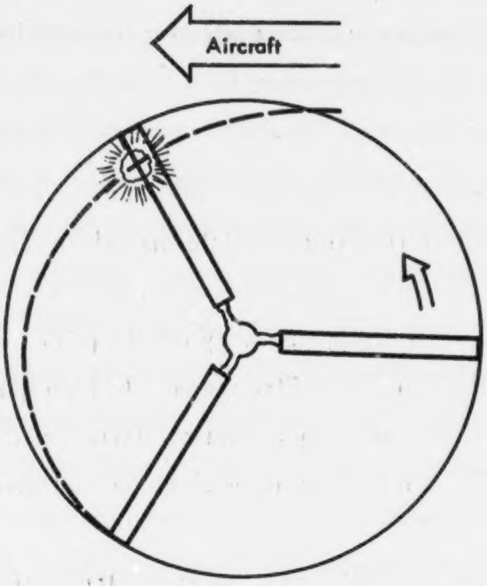
Although it is easy to imagine a blade and a tip vortex intersecting, it is extremely difficult to visualize the details of such an encounter and practically impossible to describe it mathematically. As a blade intersects or comes near a vortex filament, the blade circulation and hence the lift profile will become severely distorted. On a single rotor lift system, a blade will most likely pass near, or cut through, a tip vortex shed by a preceding blade (Figure C-12 (a)). On a tandem rotor lift system, it is more likely that one rotor will cut the vortex filament generated by the other disc (Figure C-12 (b)). The fact that large fluctuations in lift occur when a blade passes close to a vortex filament is obvious.

C.3 Internal Combustion Engine Noise

The externally-radiated noise from internal combustion engines results from a multitude of noise-generating mechanisms. Unlike the jet engine, for which one or two sources of noise dominate the noise-radiation characteristics, several noise sources contribute measurably to the noise signatures of internal combustion engines. The following major source categories are commonly recognized:

- exhaust noise
- intake noise
- engine-radiated noise due to cylinder pressure development (combustion noise)
- engine-radiated noise due to mechanical components (mechanical noise)
- cooling fan noise

(a) Single Rotor System



(b) Tandem Rotor System

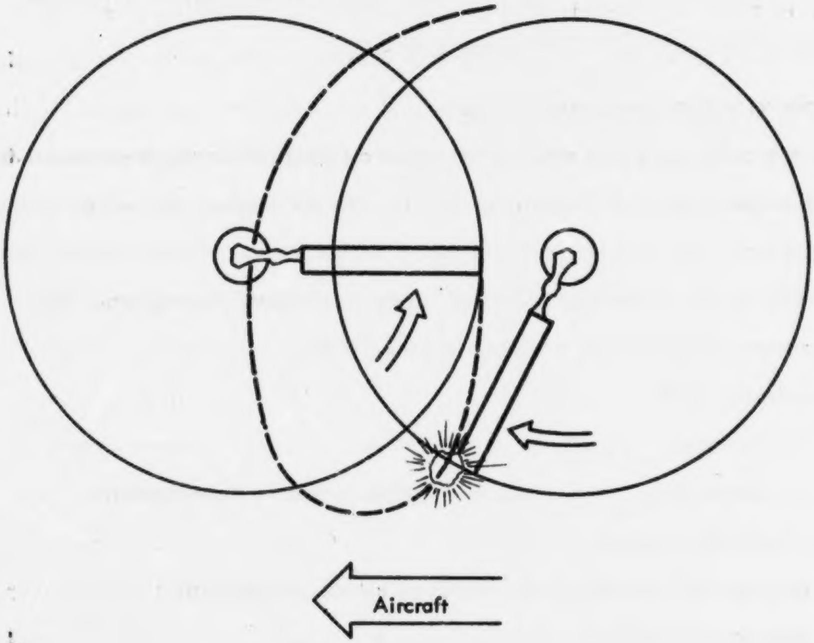


Figure C-12. Typical Blade-Vortex Intersections for a Single Rotor System (a), and a Tandem Rotor System (b) (Data from Leverton, Reference 28)

Several specific subsources are distinguished in the engine-radiated noise category. These will be discussed below in the detailed evaluation of the separate noise categories.

C.3.1 Exhaust and Intake Noise

Exhaust noise is potentially the greatest noise source of the automotive engine. It is produced by the sudden release of gas into the exhaust system by the opening of the exhaust valve. The closing of the valve produces only minor effects. The fundamentals and harmonics of the firing frequency are the principal components which have to be dealt with in the exhaust-muffler system. At high speeds, the individual frequency components are masked by a more continuous spectrum attributed to turbulence noise associated with the high velocity of the exhaust gases over the valve seat.

Intake noise is produced by both the opening and the closing of the inlet valve. At opening, the pressure in the cylinder is usually above atmospheric and a sharp positive pressure pulse sets the air in the inlet passage into oscillation at the natural frequency of the air column. The oscillation is rapidly damped by the changing volume caused by piston motion downward. Closing of the inlet valve produces similar oscillations, which are relatively undamped. In practical installations, measurements indicate that intake noise is not fully silenced and in some vehicles it is the predominant source of noise.[29]

Figure C-13 shows spectra of the noise radiation from a diesel engine running at 1500 rpm with (a) open exhaust and inlet, (b) silenced exhaust, and (c) silenced exhaust and inlet.[30] Comparison of spectra (a) and (b) shows that exhaust noise predominates by about 10 dB over the whole frequency range. Comparison of spectrum (b) with the spectrum with the air inlet silenced (c) shows that the next greatest noise source is the air inlet. The remaining noise, spectrum (c), is emitted by the engine structure itself from vibration of the external surfaces and by the cooling fan. In the diesel engine, air inlet noise generally predominates only in the low and middle frequencies, up to 1000 Hz. In the gasoline engine, this inlet noise may also

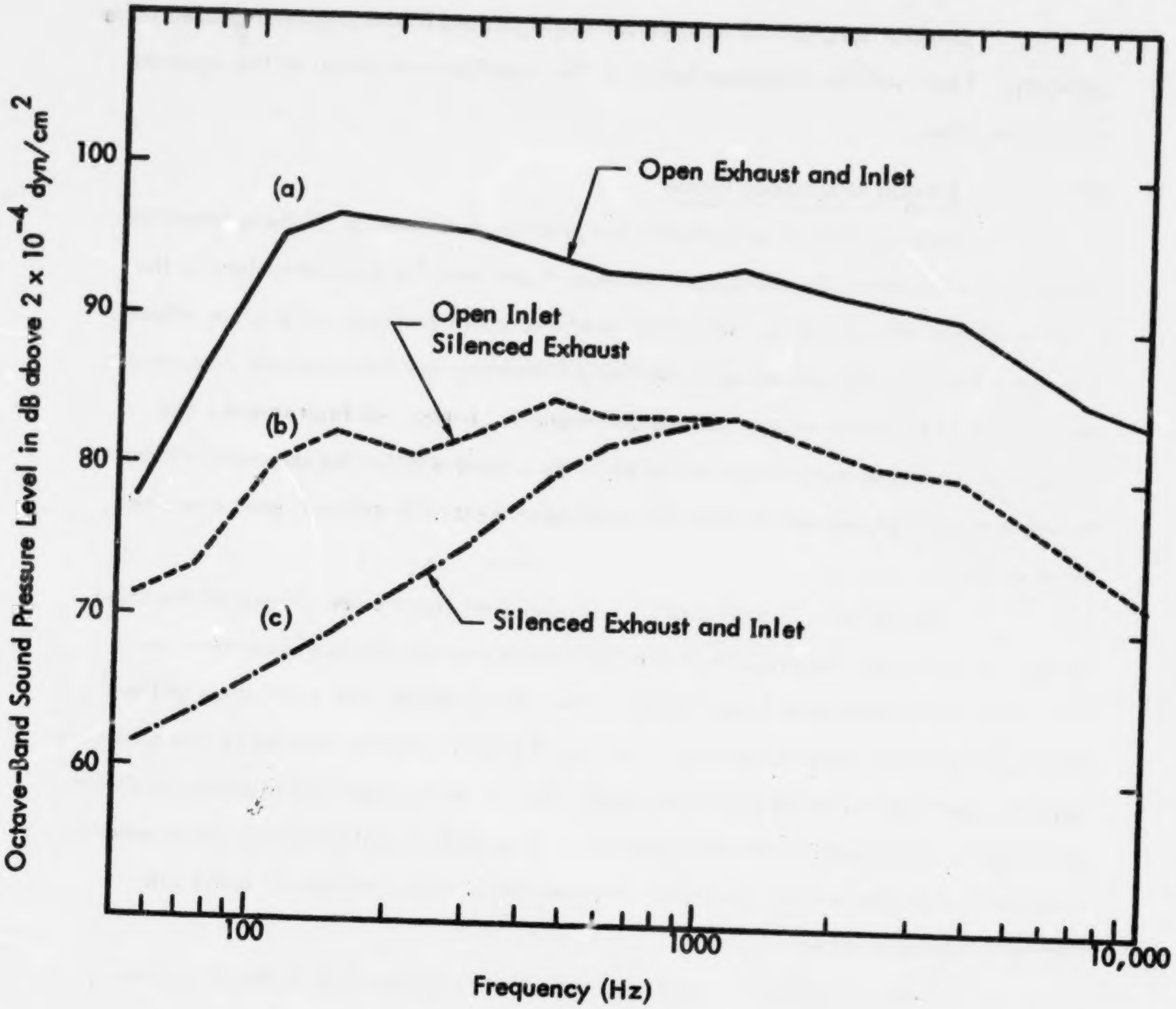


Figure C-13. Octave-Band Spectra of Inlet and Exhaust Noise of 2-Litre Diesel Engine at 1500 rpm Full Load (Data from Priede, Reference 30) predominate in the high frequency range owing to the "hissing" noise produced in the carburetor.

Both exhaust and intake noise show the same dependence on engine speed:[31]

$$\text{Sound Level dB(A)} = 45 \operatorname{Log}_{10} N + k$$

where

N = engine speed - rpm

k = undetermined parameter

The noise levels increase with increasing engine load; from no-load to full-load, the intake noise increases between 10 and 15 dB for diesel engines and between 20 and 25 dB for gasoline engines. Intake noise is also affected by the construction of the exhaust system; restrictions in the exhaust markedly increase the intake noise. Both exhaust and intake noise are greatly influenced by design variables such as the size of the valves, their timing and the construction of the parts.

Automotive engines are normally equipped with exhaust mufflers and intake silencers. In some cases these are inadequate because of space and cost limitations, even though techniques for silencing to any desired degree are well known.

Large mufflers must be used to obtain adequate silencing with low back pressures. Two mufflers in series are sometimes used (for example, on bus engines). The ratios of net muffler volume to engine displacement volume of a group of typical older passenger cars indicate values between 1.5 to 4.2. For some quieter mufflers, the volume ratio is double these values.

The location of the muffler along the exhaust pipe is important, especially with the simpler mufflers, because of pipe resonances. The most advantageous muffler location for single-muffler systems is indicated at the center of the exhaust pipe, which allows for cancellation of pipe resonances.[32]

According to Martin,[32] it has been demonstrated by experiment and theory that the direct gas flow through a muffler can considerably affect the silencing effect. Considering, first, a reactive muffler with resonant chambers and flow interruptions (staggered tubes in successive bulkheads), let D_o be the attenuation in decibels through the muffler without gas flow and D_r the practical silencing of the various frequencies with superimposed gas flow through the muffler, as measured on the actual engine. Then, as a first approximation, the following relation between D_r and D_o is given:

$$D_r = \frac{D_o}{1 - aM} \quad \text{dB}$$

where

M = Mach number of the mean gas flow in the muffler

a = nondimensional coefficient whose value falls between 1.0 to 1.2, depending on the muffler design

Thus, muffling improves with Mach number within the engine operating range and full-throttle operation is better silenced than idling operation. On the other hand, absorption type mufflers with a straight-through passage in a perforated pipe surrounded by a concentric container filled with fibrous sound-absorbing material show better silencing, D_a, at idling than at full-throttle, according to the relation:

$$D_a = D_o (1 - \beta M^{1/3}) \text{ dB}$$

Again, β is a nondimensional constant, dependent on muffler design, and falling between 1.0 and 1.2 in magnitude.

Intake silencers are usually of the straight-through design, using resonant side chambers to control both low frequency and high frequency noise, and a "hiss felt" for control of the high frequency noise spectrum. Figure C-14 shows octave band intake noise spectra at 3 feet for two diesel engines at full power, 2000 rpm operation, with normal inlet silencers and with completely silenced inlets.[33] The upper set of curves, (a), is for a 2-liter engine and includes no-load intake noise spectra. The lower set of curves, (b), is for a larger 4.2-liter engine. Intake noise on both engines reaches a substantial 95 to 97 dB peak in the low frequency octave bands at about 120 to 250 Hz at full load. The no-load intake noise octave band peak for the smaller

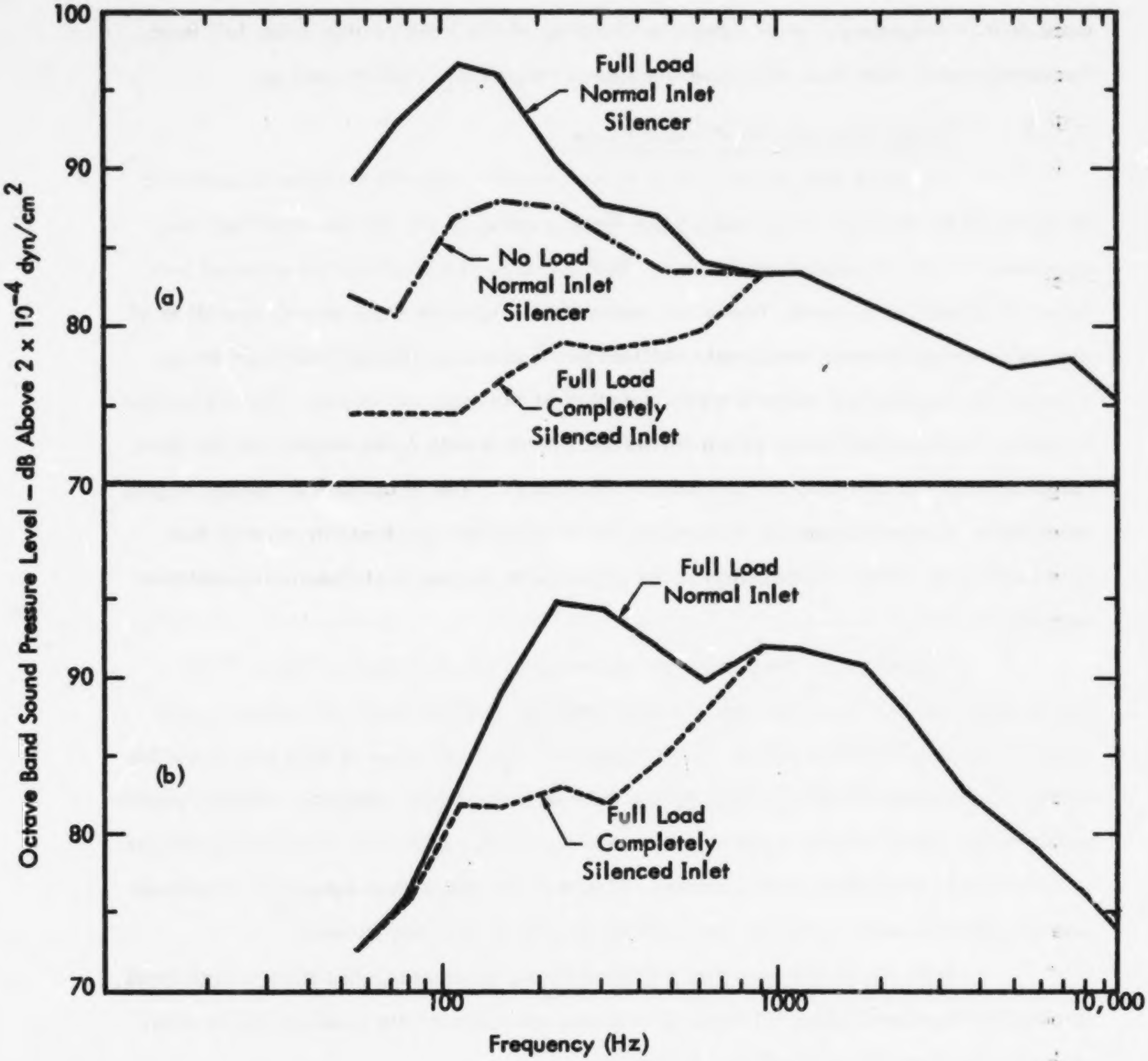


Figure C-14. Octave Band Spectra (5) of Noise of Two Diesel Engines With Normal and With Fully Balanced Air Inlets; (a) 122 cu in Engine, 2000 rpm; (b) 256 cu in Engine, 200 rpm (Data from Soroka/Chien, Reference 33) engine is about 10 dB lower (88 dB) than the full-load peak (97 dB), with a slight upward shift in frequency. With complete silencing of the intake noise under full load, the predominant noise is in the upper frequency range from 1000 Hz and up.

C.3.2 Combustion and Mechanical Noise

The noise from the structure of an internal combustion engine is produced by forces of mechanical origin and by gas forces acting on the pistons resulting from compression and subsequent combustion. Both produce vibrations of the external surfaces which emit the noise. Noises of mechanical origin are those due to operation of the piston-crank system, valve-gear mechanism, various auxiliaries and their drives. In practice, mechanical noise is defined as that of the motored engine. This definition, however, includes the effect of gas forces developed during compression; but the contribution from the compression pressure is rather small. The noise of the running engine (addition of the gas forces due to combustion) is invariably greater than that of the motored engine. Thus, combustion is the major noise source in an internal combustion engine.

The effect of combustion on engine noise is illustrated in Figure C-15 which shows spectra for diesel and gasoline engines, both motored and running, with different forms of cylinder pressure development.[33] In both types of engines, the noise can be varied some 10 dB by changing the form of the cylinder pressure. Hence, worthwhile reductions of engine noise may be attainable if the effect on noise of the form of cylinder pressure development is known. Figure C-16 shows some examples of cylinder pressure spectra from a gasoline and a diesel engine at full and no load.[33]

Both diesel and gasoline engine cylinder pressure spectra show a high level for the first few harmonics, followed by a steady decrease of the level of higher order harmonics by some 30 to 50 dB per decade.

The low frequency parts of the spectra, up to about 300 Hz or 20th harmonic, are hardly influenced by the form of pressure diagram, but are largely determined by the peak pressure. A large reduction of the level of this part of the spectrum is observed only with a considerable reduction of peak pressure such as occurs with a

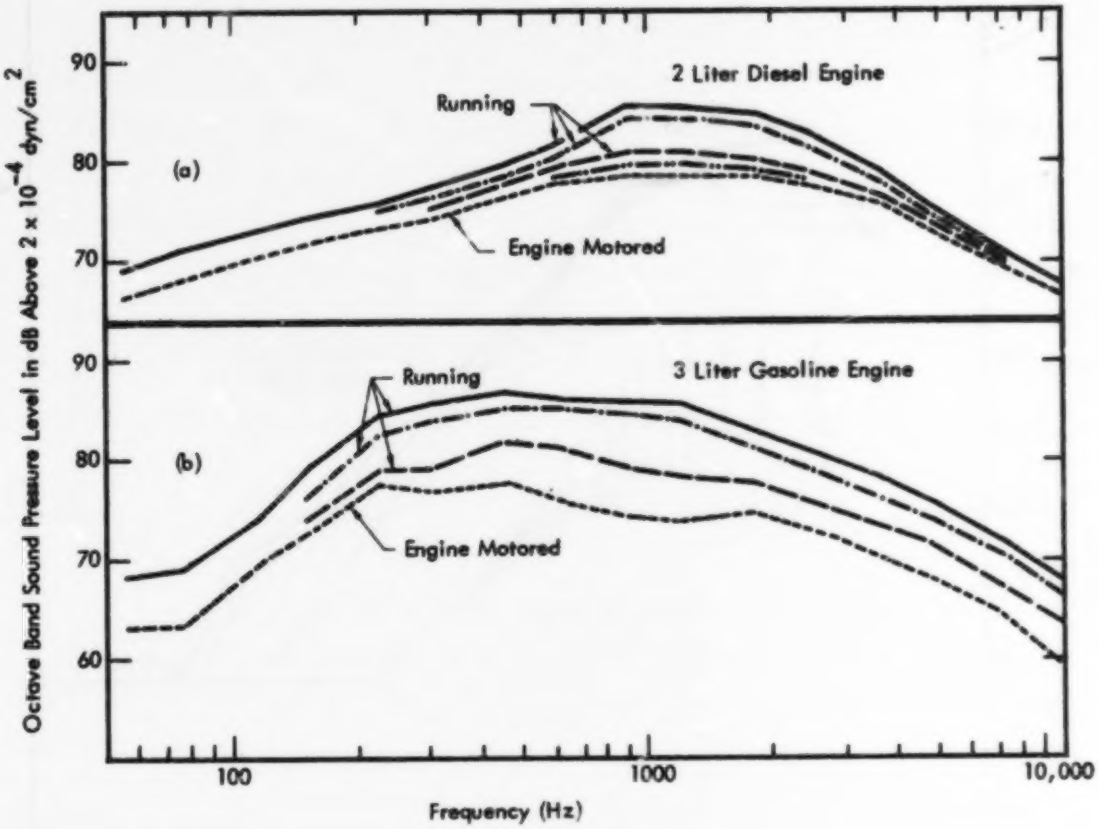


Figure C-15. Increase of Engine Noise Produced by Changes in Cylinder Pressure Development Due to Combustion at 2000 rpm; (a) Two Liter Diesel Engines; (b) Three Liter Gasoline Engine (Data from Soroka/Chien, Reference 33)

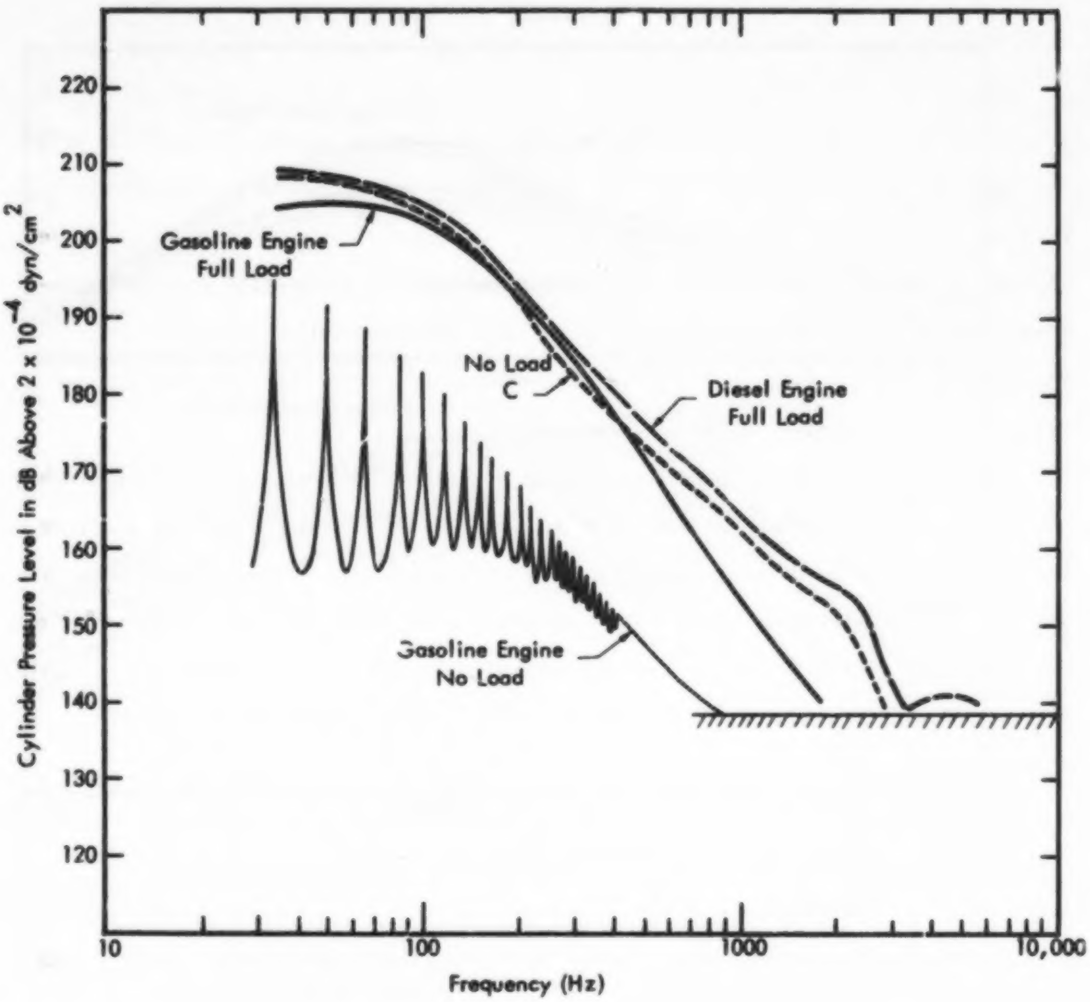


Figure C-16. Cylinder Pressure Spectra for Diesel Engine C and Gasoline Engine at 2000 rpm Full Load and No Load (Data from Soroka/Chien, Reference 33) gasoline engine on no-load. The levels of the harmonics above 20th order are affected more and more by the actual form of the pressure diagram; thus, at higher frequencies, the spectra of diesel engines diverge from those of gasoline engines and have higher levels, particularly in the range from 800 Hz to 3000 Hz.

This difference is ascribed to the different mechanism of ignition. In the gasoline engine, the flame is initiated from a spark (that is, a point source) from which the flame gradually propagates until the whole charge contained in the chamber is burned. Thus, a very smooth blending with the compression is obtained. In the diesel engine, on the other hand, ignition is spontaneous and an appreciable volume of premixed fuel and air burns extremely rapidly. This rapid combustion results in the marked discontinuity (that is, rapid initial pressure rise), invariably observed on the cylinder-pressure diagrams of diesel engines.

Noise measurements on a large number of automotive diesel engines (with inlet and exhaust silenced) have shown a striking similarity in shape of noise spectrum. All spectra show a broad peak in the frequency range from 800 to 2000 Hz, similar to that of the octave band spectrum (c) of Figure C-13. From oscillographic investigation, it has been shown that the noise is emitted in impulses coinciding with the rapid increase of cylinder pressure. It is the objectionable hard "knock" characteristic of diesel engines.

The spectrum of the gasoline engine is different. The components in the frequency range 800 to 2000 Hz are of lower intensity and the largest peaks in the spectrum are in the frequency range 400 to 600 Hz. These differences correspond exactly to the differences previously noted in cylinder pressure spectra. The different noise characteristics of diesel and gasoline engines therefore are due not to any differences of the structure but to differences in excitation due to cylinder pressure.

The effect of load on the cylinder pressure spectra (Figure C-16) is very marked in the gasoline engine, but is very slight in the diesel engine. This is due to throttling the gasoline engine intake at no-load. These observations again are found to be in agreement with noise measurements as shown in Figure C-17, where the overall

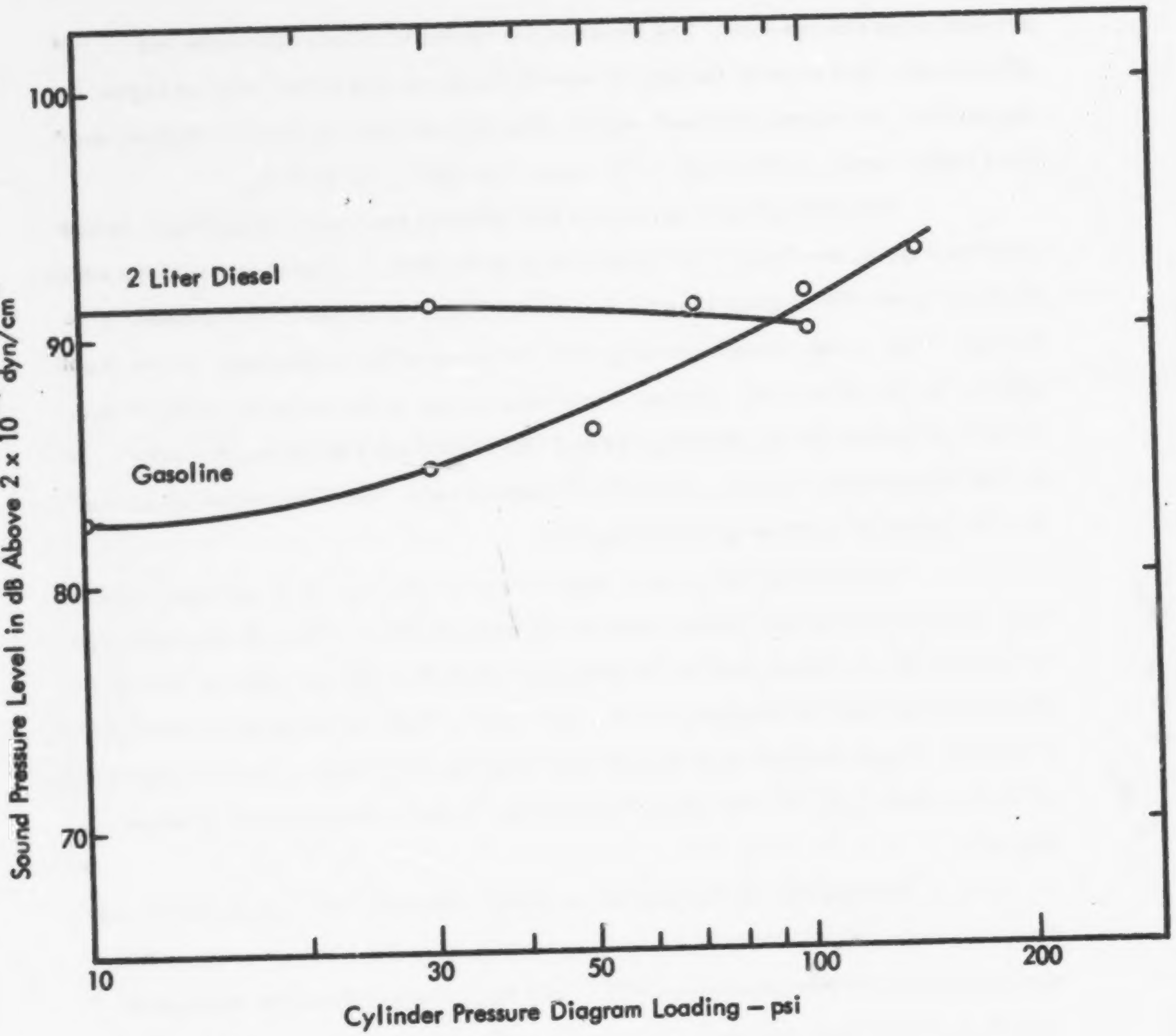


Figure C-17. Effect of Load on Overall Calculated Sound Pressure Level For a Diesel Engine and a Gasoline Engine (Data from Soroka/Chien, Reference 33) sound pressure levels are plotted against load for a diesel engine and a gasoline engine at 2000 rpm.[33] In the diesel engine, the sound pressure level at no-load differs only slightly from that at full-load; whereas in the gasoline engine, the sound pressure level at no-load is less than that at full-load by some 10 dB.

The relationship between the cylinder pressure spectrum and the engine noise radiation depends on the relative levels of the combustion and mechanical noise components. Smoothing or reducing the cylinder pressure below a certain "critical" value will have only a negligible effect on the engine noise because of the constant level of the mechanical noise.

If the cylinder pressure level is above the "critical level," the level of the emitted noise is proportional to that of cylinder pressure. This makes it possible to define the vibrational and radiating properties or the "noisiness" of an engine structure by a quantity:

attenuation in decibels = cylinder pressure level - sound pressure level

The attenuation is represented by a single curve covering the audio frequency range which is independent of engine operating conditions — speed, timing and load.

Figure C-18 shows the attenuation curves of four diesel engines and a gasoline engine of similar size (2-liter capacity).[33] As can be seen, variation of attenuation among the diesel engines of current design is not very large and the curves are found to lie within a range of some 6 dB. Also, the attenuation curve of the gasoline engine lies mainly within the group of curves for the diesel engines, which indicates that its structure is not dissimilar, as regards noise, from that of the diesel engines.

The attenuation is high at low frequencies and declines at a steady rate by about 50 dB/decade up to about 1000 Hz. Above 1000 Hz, attenuation declines at a considerably lower rate, by about some 10 dB/decade. Investigations have shows that the high attenuation at low frequencies is partly due to higher attenuation of vibration by the stiffness of the structure and partly due to higher radiation attenuation, since the wavelength of the sound exceeds that of the linear dimensions of the engine. At

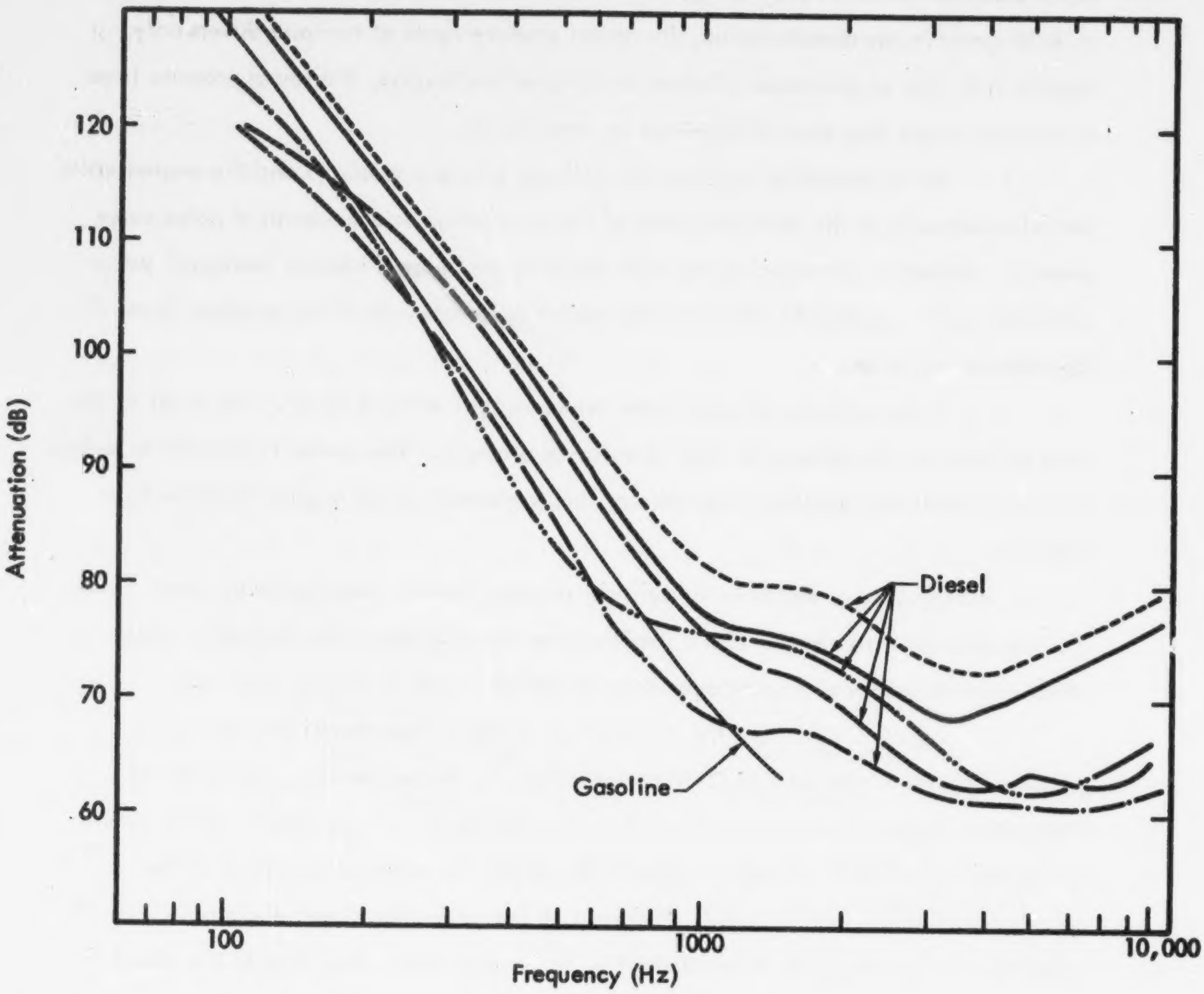


Figure C-18. Attenuation Curves for Gasoline Engine and Diesel Engines (Data from Soroka/Chien, Reference 33) high frequencies, from 800 Hz upwards, the noise is due to vibration of resonating sections of engine surfaces, generally of the crankcase, resulting from transmission of forces due to cylinder pressure both directly from and via the crankshaft.

The pressure diagram in an engine tends to remain of similar form with change of speed; therefore, to a first approximation the cylinder pressure spectra will be geometrically similar at different speeds but with a shift parallel to the frequency axis corresponding to the change of speed. Thus, the increase of engine noise will depend on the general slope of the cylinder pressure spectrum. For example, with cylinder pressure spectra having a slope of 30 dB/decade (corresponding to the slope of cylinder pressure spectra in most diesel engines), one can expect an increase of engine noise by 30 dB for the tenfold increase of engine speed.

This is confirmed by the test results shown in Figure C-19.[33] The straight lines give a good fit in the case of all four diesel engines. The noise of the gasoline engine increases in speed at a higher rate; this corresponds to the greater slope of the cylinder pressure spectrum of this engine (Figure C-16). Thus, the engine noise levels may be expressed by the simple relationships:[31]

$$\text{Sound Level dB(A)} = 30 \text{ Log}_{10}N + k \text{ for diesel engines, and}$$

$$\text{Sound Level dB(A)} = 50 \text{ Log}_{10}N + k \text{ for gasoline engines.}$$

The effect of the engine size is also clearly seen from Figure C-19. If the amplitude of vibration of engine surfaces does not vary with engine size, the increase in intensity of sound radiated should be due only to the increase in the radiating surface area and the noise would increase by 13.3 dB for a tenfold increase of engine capacity. This can be seen from the data on the few diesel engines; an increase of about 14 to 16 dB is obtained, which is very close to the above value. In general this gives the result that, power for power, a large engine running slowly is quieter than a smaller one running faster.

C.3.3 Cooling Fan Noise

Cooling fan noise is a nuisance noise in the automobile. Aerodynamic noise is generated directly through vortex formation by the fan blades. The most common type

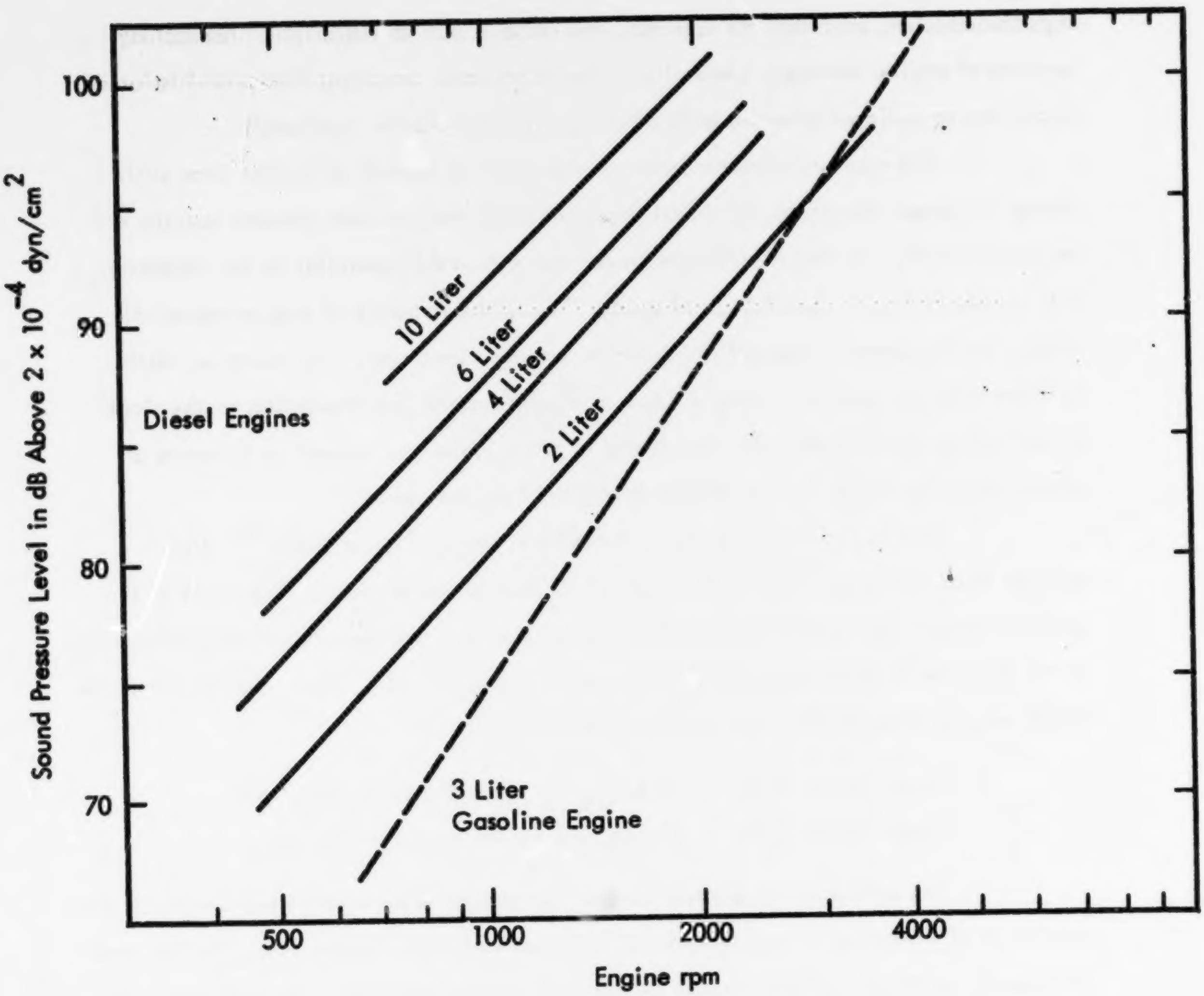


Figure C-19. Calculated Overall Sound Pressure Level versus Speed for Four Diesel Engines and Gasoline Engine (Data from Soroka/Chien, Reference 33) of engine cooling fan is the axial flow type. This is used invariably to draw air through the radiators of water-cooled engines. Centrifugal fans are sometimes used with air-cooled engines. The mechanisms of noise generation by axial flow fans have been discussed by Sharland[34] and others. These mechanisms are identical to those described in Section C.1.2 for jet engine fans and compressors and in Section C.2 for aircraft propellers and helicopter rotors, and will not be discussed separately in this section. A general empirical expression for the noise levels generated by cooling fans may be written in the form:

$$\text{Sound Level dB(A)} = 60 \log_{10} N + k$$

where

N = fan rotational speed
k = undetermined parameter

At present, the method of testing fan acoustic performance consists of installing various designs of fans which will give the required cooling, then road-testing the car at different speeds and selecting by ear the most satisfactory fan.[33] Design constraints on the fan covering space occupied, rotational speed, amount of airflow, position in car, and other factors cause difficulty in making a quiet fan.

Blade spacing can be used successfully to distribute the level of harmonics over the operating range. Four blade fans with 76 degree blade spacing have been found to be a good choice. On the average, slow running fans are the quietest. For automotive fans, noise is increased by 60 dB per tenfold increase of tip speed. Intensity is proportional to about the 6th power of rpm and therefore a special coupling to reduce fan speed at high engine speeds is one of the most effective ways of controlling the noise. Fan noise has the peculiar quality that sometimes it is difficult to mask below other car noises, particularly when the other engine noises are suppressed.

C.4 Tire Noise

Noise generated by tire-roadway interaction is one of the prime sources of annoyance for several classes of road vehicles. For example, at vehicle speeds above

30 to 35 mph, tire noise may be the principal component of the overall automobile and small truck noise spectrum. Figure C-20 shows how the engine noise levels compare with the noise levels produced by various classes of tires for a single-axle truck.[35] Although the "quiet" tires fall below the engine noise levels over the entire range of vehicle speeds, the difference in levels is sufficiently small that a moderate reduction in engine noise would leave tire noise as the principal component even for these tires, especially at the higher velocities.

The important source mechanisms in the tire/roadway interaction are:

- "Air pumping" from tread and roadway activities – the sudden outflow of air trapped in the treads or roadway cavities when the tire contacts the road surface, and the sudden inflow of air when the tire lifts away from the contact area.
- Casing vibration – excitation of the casing and tread by roadway roughness or by the tire itself.
- Aerodynamic – (a) "spinning disc" noise, (b) impingement of turbulence upon all or parts of the tire, (c) impingement of displaced air on the roadway surface.

Hayden[36] has made a detailed analytical investigation of these noise sources and concludes that the third mechanism is negligible except at very high vehicle speed. Thus, aerodynamic noise mechanisms may be considered to represent a lower bound for the tire-roadway noise.

The first two noise source mechanisms are discussed below, on the basis of Hayden's analysis.[36]

Air Pumping from Tire and Roadway Cavities

When a section of the tire tread contacts the road surface, some of the air in the spaces between the treads is displaced, thus creating a locally-unsteady volumetric flow. Similarly, when the tire rolls over and partially fills cavities in the roadway, some of the air is squeezed out of these cavities. Finally, when tire segments leave the contact area, spaces enclosed by the tire and roadway expand rapidly

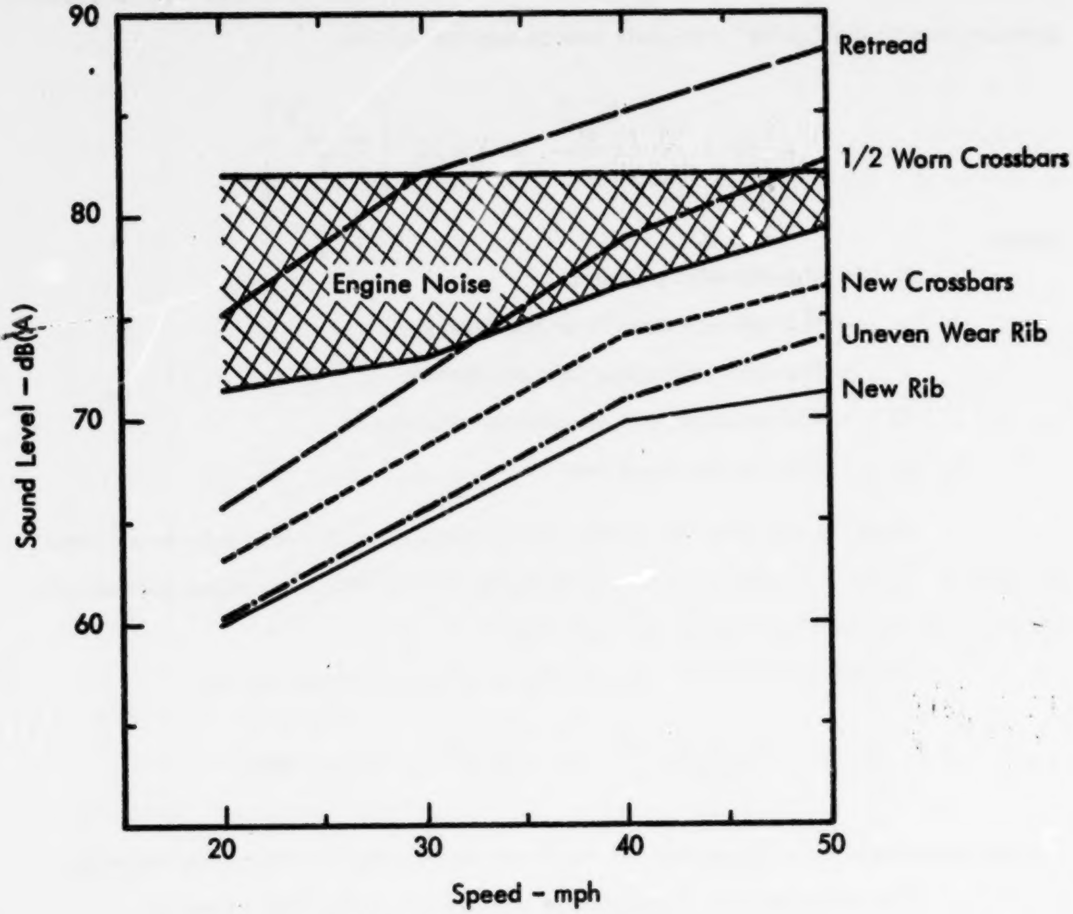


Figure C-20. The Significance of Tire Noise Relative to Engine Noise for a Typical Single Axle Truck (Data from Tetlow, Reference 35) and a volumetric flow transient is created by the air rushing to fill the expanding cavity. Such fluctuations in volumetric flow rate characterize the driving mechanisms of the acoustic monopole (or "simple source"). The narrow-band mean-square acoustic pressure due to the "point" monopole source may be written:

$$p^2(r) = \frac{\rho^2 \omega^2 \overline{Q^2}}{16\pi^2 r^2} \approx 2 \times 10^5 \left[\frac{\omega^2 \overline{Q^2}}{r^2}\right]$$

where

p = the acoustic pressure
ρ = the ambient density of the medium
r = the radial distance from the source
Q = the volumetric flow rate from the source
ω = the circular frequency

Thus, to estimate the overall sound pressure, one needs only to estimate Q and ω. Such a procedure will now be demonstrated for a tire whose geometry is shown in an exaggerated fashion in Figure C-21.

The mean-flow rate from a single cavity is estimated to be:

$$\overline{Q} = \frac{\text{Volume change}}{\text{Time}} = \frac{(\text{f.c.})gwS}{S/V} = (\text{f.c.})gwV$$

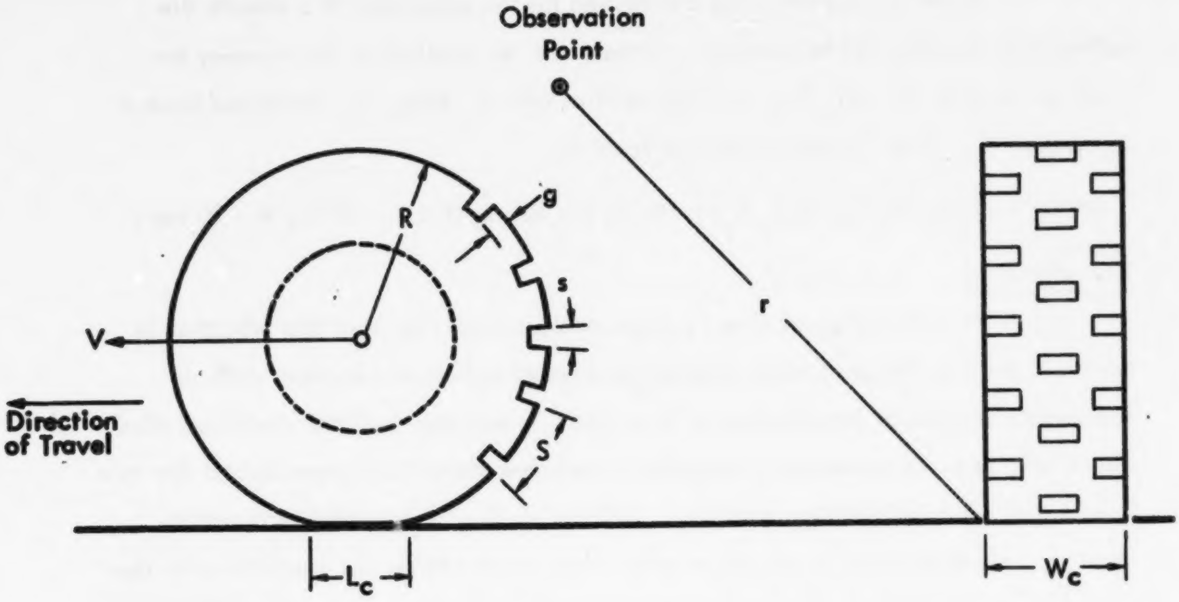
for the geometry shown (where f.c. is the fractional change in the cavity volume).

The characteristic frequency of occurrence of the flow pulse is:

$$\omega = 2\pi V/S$$

By substituting these relationships into the first equation and taking the logarithm with respect to the reference pressure 0.0002 μbar, the following "engineering equation" is derived (for n cavities per tire width):

$$SPL(r) = 68.5 + 20 \log (gw/S) + 10 \log n + 20 \log (\text{f.c.}) + 40 \log V - 20 \log(r)$$


Observation Point
R
g
s
V
Direction of Travel
S
r
L_c
W_c

V = forward velocity
W = width of a single cavity or groove in tread
g = depth of groove = tread depth
S = circumferential distance between tread grooves
s = circumferential dimension of tread grooves
R = tire radius
r = distance to observation point

(Note: The respective values of W, g, S, and s on a given tire may be different for individual cavities.)

Figure C-21. Tire Terminology
(Data from Hayden, Reference 36)

This equation is valid for the case of a non-directional sound source and hemispherical spreading.

A similar equation may be derived for the sound due to a smooth tire rolling over cavities in the roadway. If there are m cavities in the roadway per width of the tire $(m = W_c/S_r)$ and the cavities are d_r deep, w_r wide and have a spacing of S_r, then the sound pressure level is:

$$SPL(r) = 68.5 + 20 \log (d_r w_r/S_r) + 10 \log n + 20 \log (f.c.) + 40 \log V - 20 \log r$$

Tire Vibration

The excitation of tires by road roughness and resultant tire vibration is complex, making the prediction of associated sound radiation somewhat difficult. Reasonable analytical formulations of tire vibration and the resultant sound radiation would require much presently unavailable knowledge about tire dynamics and dynamic behavior of the tire/roadway interface. With so much of the needed information lacking, an experimental approach may be taken to determine the roadside noise due to tire casing vibrations. The empirical curve for predicting sound radiation from the acceleration input spectrum shown in Figure C-22 was obtained by placing a tire in a reverberant chamber and measuring the sound power level spectra for various vertical input acceleration levels and spectra.[36] It may be noted that the tire responds strongly within a range of frequencies from 125 to 1000 Hz. The cut-on at 125 Hz corresponds roughly to the fundamental resonances of the tire. Above 1000 Hz, the input acceleration levels are strongly damped.

Vibrational sound from a passenger car tire operating on a granite chip road surface has been predicted with the use of Figure C-22 from indirectly-measured acceleration spectra.[36] The resultant sound power spectra are shown in Figure C-23 and the overall levels at various speeds in Figure C-24.

The relative importance of each of the previously discussed source mechanisms to the overall noise radiated by a rolling tire may be estimated from the relationships developed above. For several different tires and road surfaces, the

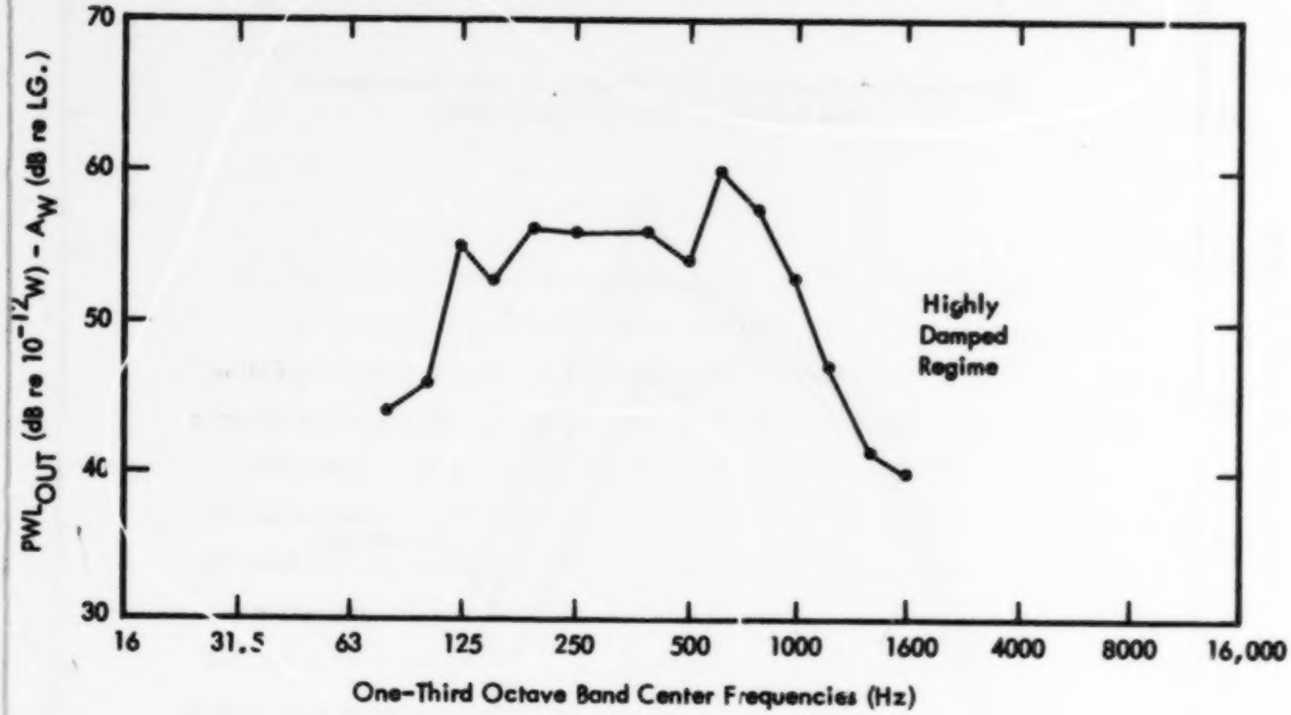


Figure C-22. Empirical Curve for Predicting Sound Radiation from Acceleration Input Spectrum (Data from Hayden, Reference 36)

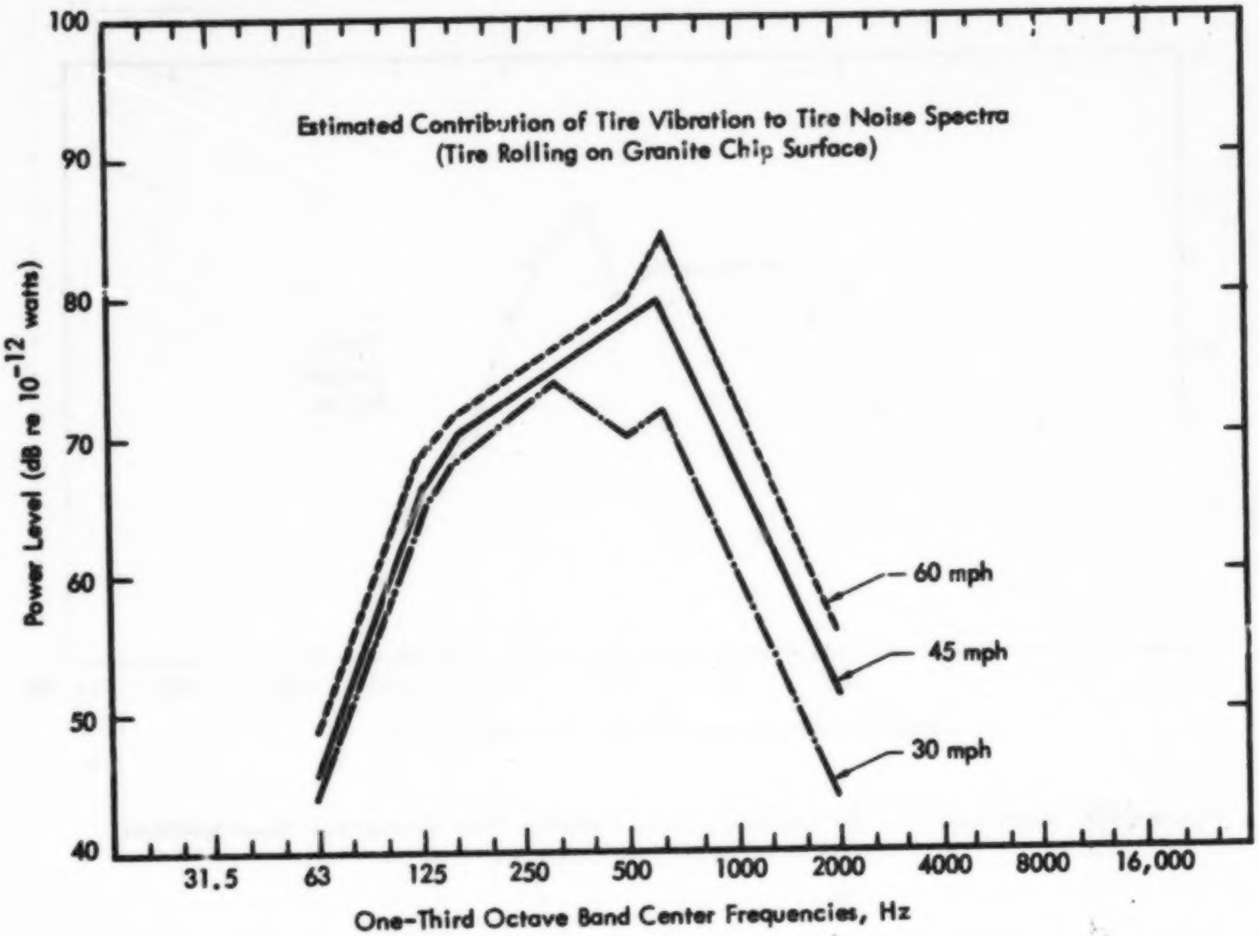


Figure C-23. Estimated Contribution of Tire Vibration to Tire Noise Spectra
(Tire Rolling on Granite Chip Surface)
(Data from Hayden, Reference 36)

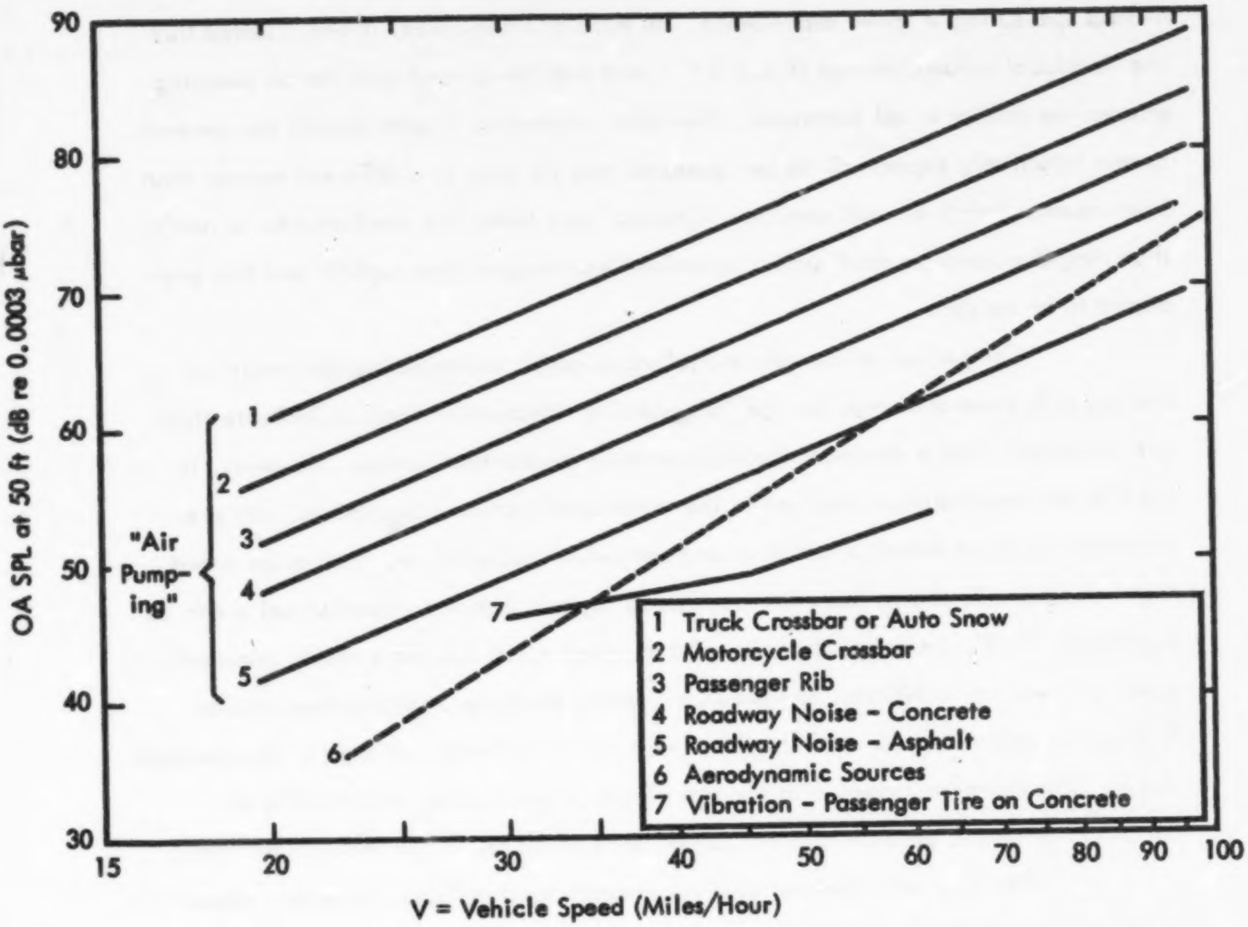


Figure C-24. Predicted Contribution of Various Source Mechanisms to Roadside Noise (Data from Hayden, Reference 36) appropriate geometrics have been determined for predicting roadside noise from the "air pumping" mechanism.[36] The results are shown in Figure C-24. Curves 1 to 5 all exhibit the 40 log V speed dependence. In each of these cases, it was assumed that the fractional volume change (f.c.) is 0.1 and that the dynamics of the air pumping process are similar in all instances. The latter assumption is undoubtedly too general, as one intuitively expects air to be squeezed from rib tires in a different manner than from crossbar treads or road cavities. Crossbar type treads are predicted to be noisier than ribs; the concrete road surface examined was rougher than asphalt and thus predicted to be noisier.

Comparison of the vibrational sound levels estimated by the empirical method with those estimated for the "air pumping" mechanism tends to indicate that tire vibration is not a dominant sound-generating mechanism in tires. However, in view of the uncertainties involved in the input acceleration calculations, this prediction must be regarded as tentative and somewhat inconclusive. It may be noted that measurements of tire noise on rough roads suggest that tire vibration noise can be significant.[31] The noise spectra measured on rough roads showed a nearly constant spectrum level up to 800 Hz, followed by a strong decrease at higher frequencies. Changes in vehicle speed were found to result in no significant change in the spectrum shape. This behavior agrees with the tire vibration mechanism, whereas the air pumping mechanism predicts a linear dependence of frequency on the vehicle speed.

The data obtained on relatively smooth road surfaces, however, appear to agree with the predictions of the air pumping model in several respects. Evaluation of Tetlow's data,[35] shown in Figure C-20, confirm the following trends:

- Speed dependence of the measured sound approached 40 log V, especially at the higher speeds.
- Crossbar treads were found to be noisier than rib-type treads.
- Cup-type treads which completely seal upon contacting the road were the noisiest; this suggests that the ωQ term is the greatest for treads which completely seal, thus the higher acoustic intensities from the monopole or "air pumping" sound.

These conclusions are further supported by the data of Figure C-25,[35] which show that a 15 dB drop in noise level resulted when a single-axle truck was unloaded; load per tire was decreased from 4550 to 1240 pounds. This effect is simply explained: with the truck unloaded, the sides of the tire tread do not touch the ground and hence the cups in the tread cannot seal against the road surface. Recent data obtained by Hayden[36] for the tire noise generated by a coasting automobile show both the 40 log V shift in overall level and the linear shift in frequency with vehicle speed predicted by the air pumping model.

Hence, it appears that this mechanism of noise generation may be adequate to explain the tire noise radiation measured in tests over relatively smooth road surfaces for a considerable range of vehicle speeds and tire configurations. The importance of tire vibration noise has not been satisfactorily resolved.

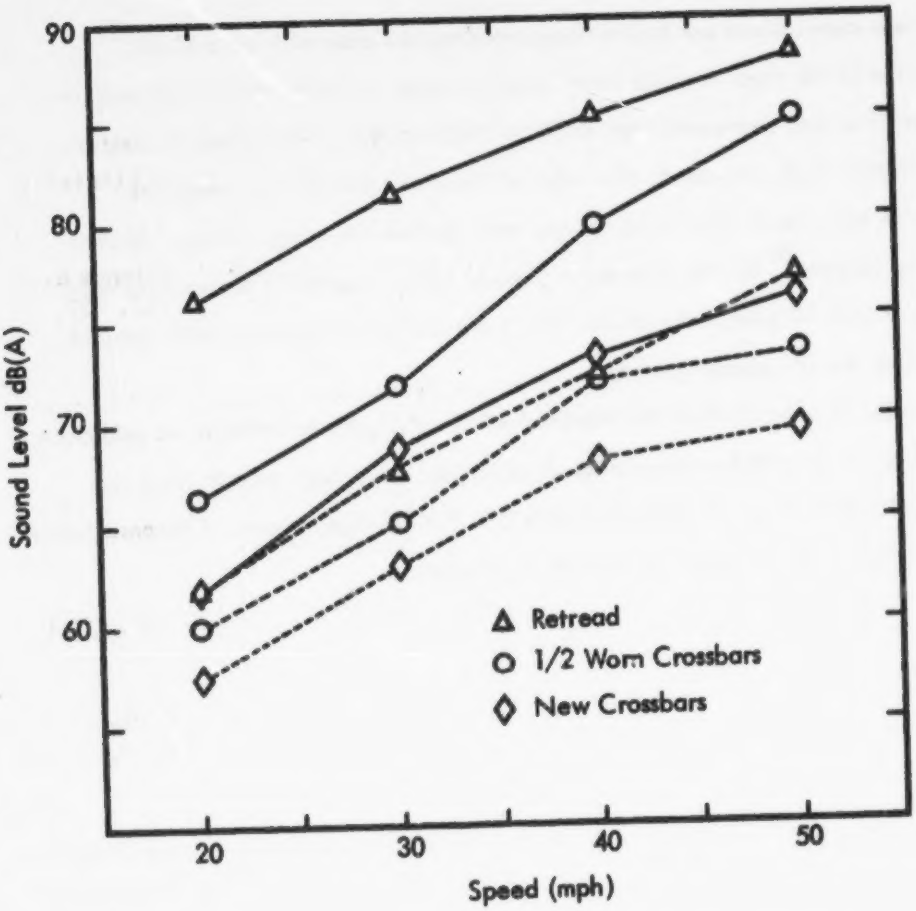


Figure C-25. The Effect of Load on Tire Noise. Solid line represents maximum tire load (4500 lbs); dashed line represents minimum tire load (1240 lbs). (Data from Tetlow, Reference 35)

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